FINAL REPORT

Distributed Storage Inverter and Legacy Generator Integration Plus Renewables Solution for Microgrids

ESTCP Project EW-201245

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14. ABSTRACT
The objectives of this project were to demonstrate the ability to operate a microgrid with less expensive power storage instead of large scale energy storage and that the renewable energy with small-scale power storage can maintain power quality in islanded mode with minimal use of the generators during non-optimal (e.g. cloud covered) periods. A 400kW microgrid application employing power optimized energy storage, transient rated storage inverter, microgrid enabled PV inverters, relatively high percentage PV energy source component as well as modified legacy natural gas (NG) generator control were successfully demonstrated. The demonstrations showed that power optimized, in conjunction with NG generators and renewables, can support an islanded microgrid without loss of power quality, staying within per IEEE-STD-1547 voltage and frequency limits. This includes the case an unintentional island, where grid is lost and generators were off. The demonstrations also showed that high penetration PV along with power optimized storage can power an islanded microgrid, and supplement generators while maintaining a stable voltage bus.

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ACRONYM LIST

Battery Management System	BMS
Central Energy Plant	CEP
Engine Control Units	ECU
Integrated Alternative Power Systems	IAPS
Kilo Volt-Amperes Reactive	kVAR
Kilo Watts	kW
Lithium Ion	Li Ion
Lithium-Titanate Oxide	nLTO
Natural gas	NG
Performance Objectives	PO
Photovoltaic	PV
Power Factor	PF
Power Quality	PQ
Solid electrolyte interface	SEI
State of Charge	SOC
Underwriters Laboratories	UL
Uninterruptible Power Supply	UPS
Zinc Bromide	ZnBr

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EXECUTIVE SUMMARY

Current microgrid designs integrating distributed generation and renewable energy sources require large scale energy storage, typically in the form of batteries, to enable a high power quality transition to islanding. These energy storage systems, however, are prohibitively expensive and will slow the application of microgrids at U.S. installations. The Eaton solution replaces these oversized and expensive systems with a power storage approach at lower cost and comparable performance.

The project had two main objectives:

1. Demonstrate the ability to operate a microgrid with less expensive power storage instead of large scale energy storage.
2. Demonstrate that the renewable energy with small-scale power storage can maintain power quality in islanded mode with minimal use of the generators during non-optimal (e.g. cloud covered) periods.

A 400kW microgrid application employing power optimized energy storage, transient rated storage inverter, microgrid enabled PV inverters, and a relatively high percentage PV energy source component as well as modified legacy natural gas (NG) generator control was successfully demonstrated. The microgrid load and some of its auxiliary equipment is an air conditioning chiller. This chiller system presents a variable load up to 350kW. Figure 1 depicts the major components of the power optimized microgrid and the associated three phase power connection scheme.

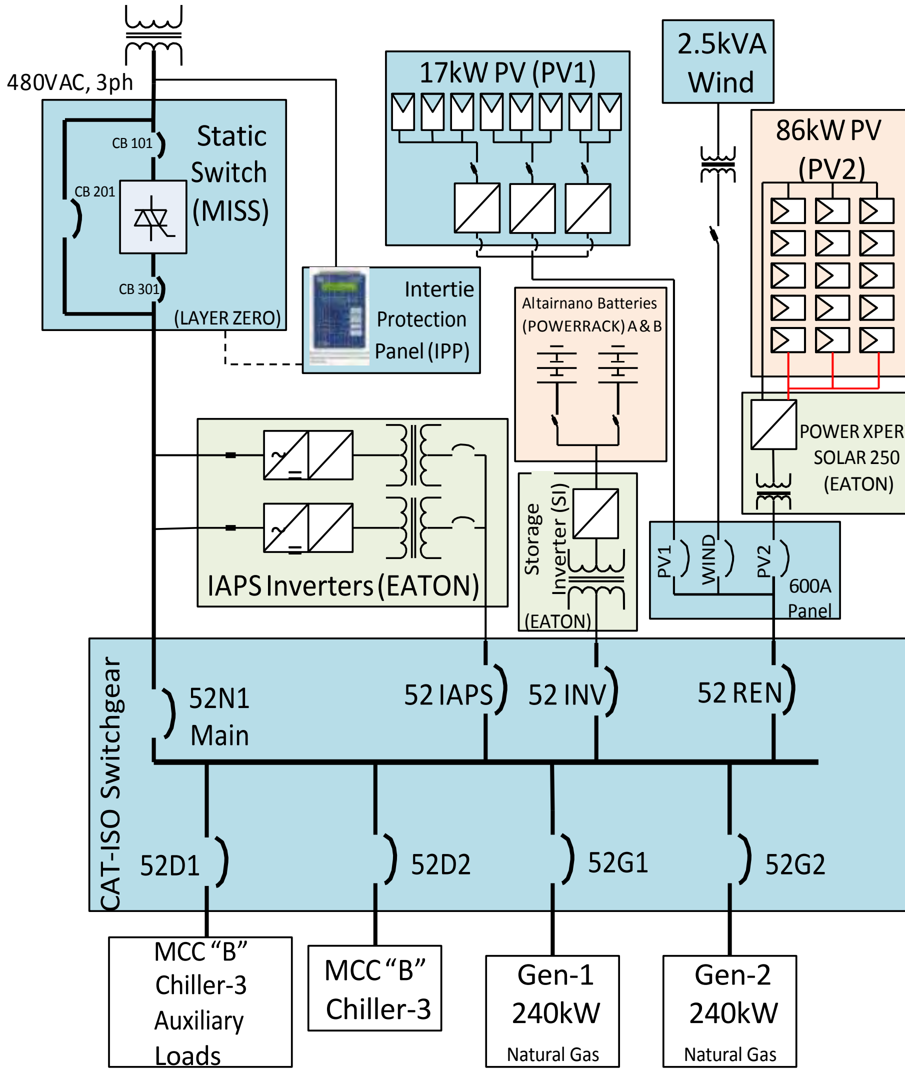

Figure 1: Fort Sill Microgrid System One line Diagram

The demonstrations were successful, and showed that power optimized, in conjunction with NG generators and renewables, can support an islanded microgrid without loss of power quality, staying within IEEE-STD-1547 voltage and frequency limits. This includes the case of an unintentional island, where grid is lost and generators were off. The storage system powers the load until generators go online, with generator synchronization being faster due to the stable bus provided by the storage system. The demonstrations also showed that high penetration PV along with power optimized storage can power an islanded microgrid, and supplement generators while maintaining a stable voltage bus.

Compared to energy optimized storage, the power optimized storage system proved to be 33% of the cost and 13% of the volume. This will enable greater acceptance and penetration of microgrids, as energy storage is typically the most costly required new equipment for a high performance microgrid.

1 INTRODUCTION

Current microgrid designs integrating distributed generation and renewable energy sources require large scale energy storage, typically in the form of batteries, to enable a high power quality transition to islanding. These energy storage systems however, are prohibitively expensive and will slow the application of microgrids at U.S. installations. The Eaton solution replaces these oversized and expensive systems with a power storage approach at lower cost and comparable performance.

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1. Demonstrate the ability to operate a microgrid with less expensive power storage instead of large scale energy storage.
2. Demonstrate that the renewable energy with small-scale power storage can maintain power quality in islanded mode with minimal use of the generators during non-optimal (e.g. cloud covered) periods.

The project was conducted in two phases:

Phase 1 focused on:

- Demonstration site survey, preparation, and demonstration plans
- System design, equipment purchase and assembly, design modifications, update inverter code, and site installation

Phase 2 focused on:

- Conducting site microgrid operations to demonstrate different features and to gather performance data
- Analysis and summary of data, and a quantitative and qualitative analysis of the results

The demonstration allowed seasonal samples during the annual solar cycle, showing that improvement in power surety can be achieved (by adding a reduced capacity power storage to a legacy natural gas engine/generator) and that a renewable energy dominated microgrid is possible, reducing fossil fuel based sources.

1.1 BACKGROUND

The Department of Defense (DoD) is developing energy strategies for installations that include the increase of alternative energy and renewable energy supplies. As these additional resources are combined with the existing utility and backup power systems, a coordinated approach is needed to optimize energy for surety, reliability and safety while minimizing cost and environmental impact. The microgrid is the solution for this balanced system of systems, and is an enabling platform to “Island” critical missions for energy surety. The problem today is large scale implementation of microgrids currently cannot draw upon commercially available components and the microgrid system scale-up is limited by the high cost of the required energy storage (the highest cost element in a microgrid).

Currently, microgrids for energy surety use centralized large energy storage systems at a high cost as diesel and gas generators cannot support the transition to islanding. Rotating reserve could also provide this "storage" but they are undesirable as they require inefficient 24-hour operation of generators and have a single point of failure. The solution demonstrated uses power optimized energy storage modules; these are co-located and integrated with the distributed generators. This integrated storage generator system has the benefits of minimum battery size and cost (requiring only one minute of storage to bridge the time for a generator to parallel with the microgrid), allows the application of a small and lower cost transient rated inverter (advantage of short term storage) and enables microgrid upgrade of legacy generator assets (integration of inverter and generator controllers). This solution reduces storage costs by 67%, with a large increase in reliability. (See Performance Objective "Procurement Cost Reduction of Storage" in Section 3.1)

The integrated power optimized storage and legacy generator solution provides a commercial path for converting existing distribution systems into microgrid capable systems. The solution achieves high power quality, ride-through, fast-acting transient real and reactive power support and will enable islanding of microgrids. This eliminates the cost impact of massive battery energy storage (>67% cost reduction), the complex upgrades to legacy generators for microgrid performance and replaces them with lower cost power optimized storage in the microgrid system. The energy storage system used is commercial off-the-shelf technology and is approximately 33% of the cost of typical battery energy storage solutions deployed today. The storage inverter controls and hardware are also leveraged to provide an islanding inverter (microgrid compatibility) for renewable energy sources (PV for this program), which maximizes the effective load carrying capacity of the renewable energy source when grid connected or islanded, and reduces generator fuel consumption.

1.2 OBJECTIVE OF THE DEMONSTRATION

The first objective of the project is to demonstrate the ability to operate a microgrid with natural gas generators without large scale battery energy storage. A power storage system (with approximately 1 minute of capacity): enables the generators to rapidly synchronize to the inverter and power the islanded microgrid; support grid stability by providing transient power (real and reactive); and support PV power transitions to maintain a stable islanded microgrid.

The second objective of the demonstration is to show that the renewable energy can maintain power quality in islanded mode with minimal use of the generators during non-optimal (e.g. cloud covered) periods. The demonstration features a large (relative to the overall system power requirements) photovoltaic solar array, whose inverter is configured to provide generator like operation, including VAR support (reactive power) for microgrid voltage stability.

- Validate: This project demonstration provides field data from an actual microgrid site, that validates the ability of power optimized storage to support legacy generators in providing power surety. It provides data that supports stable operation of high penetration PV within a microgrid.

- Findings and Guidelines: The demonstration data will enable subsequent microgrid installations to be optimized for surety and cost with the technologies being demonstrated.
- Technology Transfer and Acceptance: The team provides an analysis of application areas within the DoD infrastructure, including an assessment of where power storage (short term) is applicable versus energy storage (long term) and the cost benefits that can be derived. This will provide data supporting the expected DoD benefit of the technology, as well as the technology transition.
- Additional Benefits: This project allowed Eaton to demonstrate advanced PV control methods that will benefit both industry and Eaton in expanding PV penetration with stability. The project also demonstrated power optimized storage, which will enable more options and broader application of new storage technologies.

1.3 REGULATORY DRIVERS

The Department of Defense (DoD) spends approximately $4 billion per year on facility energy consumption to power and fuel over 500 military installations worldwide. These installations include over 500,000 buildings and structures as well as 160,000 non-tactical vehicles.

The purpose of ESTCP Installation Energy Technology demonstrations is to accelerate the deployment of innovative energy technologies that target DoD needs. ESTCP demonstrations are conducted under operational conditions at DoD installations. The demonstrations are intended to generate supporting cost and performance data needed for validation of the technology. The goal is to enable promising technologies to receive end user acceptance and be fielded and commercialized more rapidly.

The Department has three key installation energy goals:

1. Reduce energy usage and intensity
2. Increase renewable onsite energy generation and
3. Improve energy security

Achieving these goals cost effectively will require the increased deployment of advanced technologies. ESTCP energy demonstrations are designed to meet these goals. Demonstrations of energy technologies on military installations should accelerate the broader deployment of the innovative energy technologies across DoD by reducing real and perceived risks. Newly developed pre-commercial and emerging commercial technologies are of interest.

The demonstrations showed technologies that enable stable operation of microgrids with a high penetration of renewables (in this case PV), and lower cost energy surety by using power optimized storage.

The DoD Strategic Sustainability Performance Plan specifically calls out the following mandates:

- Executive Order (EO) 13514: Articulates both general and specific requirements to improve federal government efficiency through the development of a green economy and a decreased dependence on fossil fuels. The DoD Strategic Sustainability Performance Plan (the Plan) provides a coherent approach both for complying with multiple federal requirements for sustainability and for assuring the mission. The linkages between sustainability and the DoD mission are strong and direct. There are four key areas of intersection that form priorities for the Department:
    1) Energy and Reliance on Fossil Fuels
    2) Chemicals of Environmental Concern
    3) Water Resources Management
    4) Maintaining Readiness in the Face of Climate Change

- Executive Orders 13423 & 13514: ‘‘Sustainability” and “sustainable’’ mean to create and maintain conditions, under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic, and other requirements of present and future generations of Americans. In January 2010, the Department released an aggressive target under EO 13514 for reducing direct greenhouse gas emissions from facilities and non-tactical fleet vehicles. These emissions are overwhelmingly due to direct energy use, especially electricity.

The technologies demonstrated microgrid operation with less generator run time, and lower fuel consumption due to the contribution of the system’s PV. This results in lower emissions and greenhouse gases.

2 TECHNOLOGY DESCRIPTION

This project's solution is a power optimized storage approach to microgrids that replaces today's approach of long term energy storage with (legacy) generators primarily off-line and intermittent renewable sources like PV. This alternate storage solution is suitable for deployment over a wide area and will provide higher reliability, energy surety, and minimize the need for load dedicated storage (i.e. UPS). The technologies employed in this solution are power delivery optimized storage, transiently rated inverters, integration with legacy generator controls, and microgrid compatible inverters for PV. Key system design drivers are lowering microgrid implementation costs and improving legacy generator performance.

2.1 TECHNOLOGY OVERVIEW

Performance of natural gas generators in microgrid applications

Natural gas (NG) generators are well suited for modern microgrids because of their low emissions and cost. NG generators are also ideally suited for energy surety and security of military microgrids. However, NG generators (and modern diesel generators meeting emissions requirements) cannot synchronize quickly, connect to other online generators or respond to fast load transients. When dissimilar generators (generators of different kW ratings or generators with different fuel types) are operated in parallel similar performance degradation is common. Since microgrids will likely be formed out of existing legacy generators that could be of different sizes and different fuel types, addressing these transients is critical [1]. Figure 2 shows the frequency and voltage of a NG generator during a 100% step load typically required for microgrid applications. The settling time (the time it takes for the frequency and voltage to be stable after a step load) for NG generators could be 30 sec to 1 min (diesel generators kept warm settle within 15 sec). The response of natural gas engines pose a problem when operating in a microgrid with diesel engines and inverter based renewables when the frequency and voltage are not stable. The second or third generator that has to come on-line takes time to synchronize to the fluctuating frequency and voltage from the generators already online. This poor performance can cause certain critical equipment to go off-line since the voltage is out of range, or the UPS's on critical loads to go into battery mode whenever a load transient occurs. As a result of this, large capacity battery storage with large inverters has been needed to support the load while the generators are sequentially synchronizing and coming online.

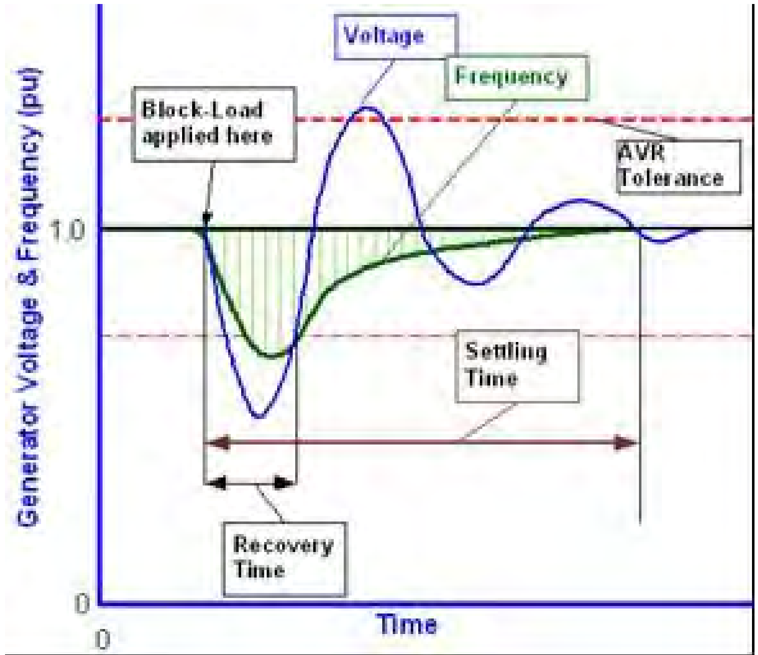

Figure 2: Frequency and voltage variation under step loading

Performance of renewables in microgrid applications

Renewable energy sources such as Solar PV, Solar Thermal, and Wind are seen to be important for energy surety of military posts and such critical facilities. This is more so since the cost of PV has dropped (present cost of installation is $4/W compared to $11/W in 2004). However, all renewables are intermittent by nature and their energy output cannot be forecasted. To address the gap between the availability of these sources and the demand, several studies have proposed large energy storage to fill the energy gaps and to enable renewables to be more dispatchable. The size and cost of the large centralized energy storage is cost prohibitive for an economical prime-time microgrid solution. An alternative to large energy storage batteries powered with large energy storage inverters is demonstrated here. Typically a NG or diesel generator is present in the microgrid energy sources and the need for battery energy storage can be met with these generators if the transient capabilities of the generators are managed. The transients are typically of short durations (tens of seconds), and can be managed with the planned microgrid enabled controls.

Transient Rated Inverter

As seen in Figure 3, in a distribution system when the microgrid is islanded by opening the upstream static switch, the inverter with power storage supports the load, adds system stability and transfers it to the generator(s). This smooth transfer enables other generators to connect to the microgrid as the frequency and voltage swings are managed. These generators can synchronize simultaneously (rather than sequentially over a longer time, as presently done). Given this stable microgrid voltage, frequency and rapid synchronization, the time (and energy) to support the load is shown to be small, less than one minute (even for NG generators).

An example of the power transitions for the proposed power storage inverter with generator is shown in the following figures. The simulation results are for the case of a 150kW load (0.8 pf load) being initially supplied by the utility, with an inverter on line and a 190kW generator off line. At time 1.3 seconds the utility connection is opened. As Figure 4 shows inverter immediately supplies load power (kW). The generator is up to speed and synchronizes at 19 seconds. Its power is ramped up (by increasing generator frequency) over 10 seconds. At 30 seconds the generator is fully powering the load, and the inverter is slowly charging.

Figure 4 shows the corresponding reactive power (kVARs) transition from utility to inverter to generator. In this case the inverter and generator are sharing VARs. VAR support does not place any demand on the inverter storage element (e.g. Li-ion battery), and allows for rapid voltage support when necessary.

For this case the inverter only needs to supply real power (kW) during a 30 second transition while the generator is turned on and brought on line. The load is continuously powered with no significant perturbations.

Note that there is a slight power transient when the generator switches on line at 19 seconds. However, the inverter compensates for the generator induced transient. The result is that the microgrid load will not experience any significant perturbation, since the transient event is confined to the inverter+generator combination.

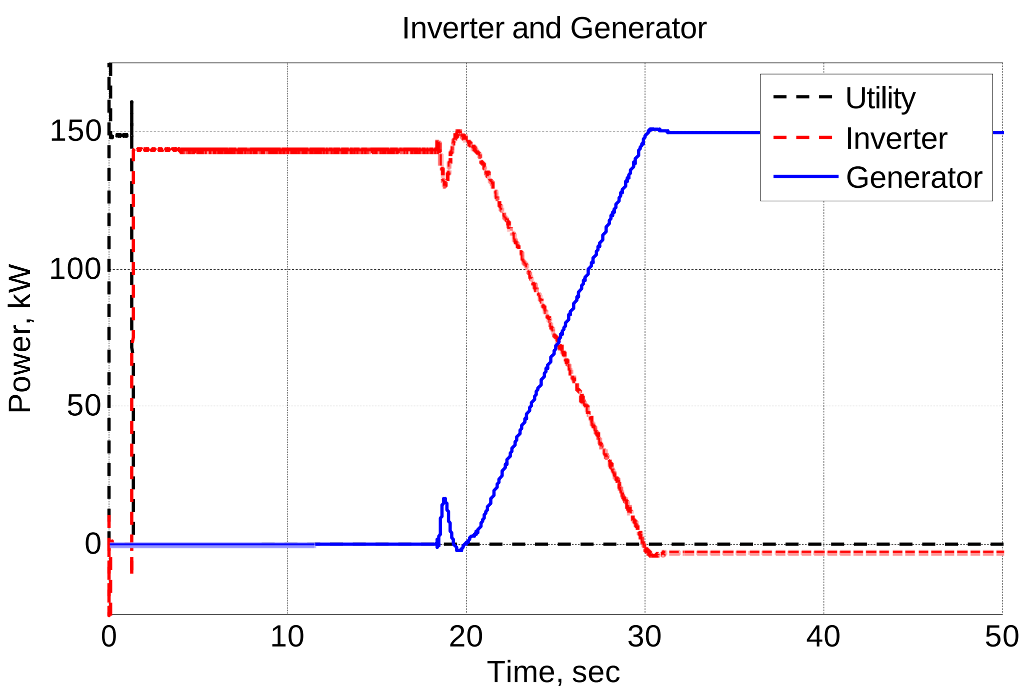

Figure 3: Power During Utility Generator Transition

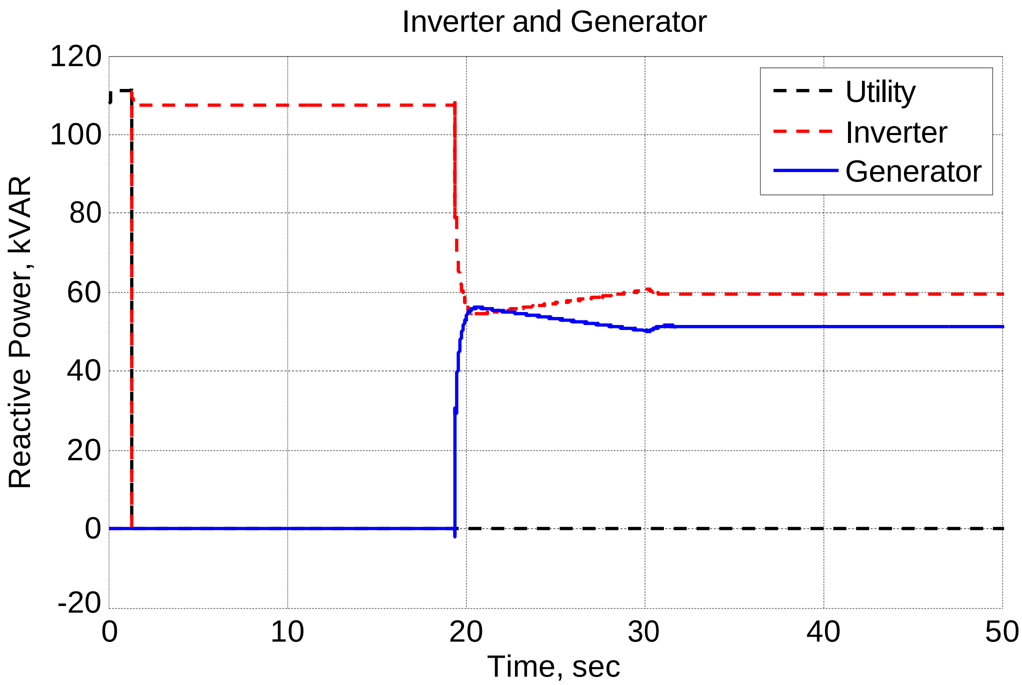

Figure 4: Reactive Power during Utility Generator Transition

A further application of the inverter is to upgrade the generator controls for microgrid capability (e.g. shared data with inverter, and genset P and Q dispatching). Legacy generators do not typically provide this microgrid compatible performance and since they do not have the communication capabilities, there is a need to upgrade the engine and exciter controls, and provide microgrid capable controls. The inverter will communicate with the microgrid and modify the behavior of the legacy generator to mimic a microgrid compatible generator. As an example, when the legacy generator has to support a transient kW or kVAR, the transient rated inverter will provide the transient power and the legacy generator will not need the performance enhancements. Another common and more serious condition occurs during loss of load during which the generator can trip on a reverse power condition.

Since the required short-time energy storage is small and can be integrated with the generator, a legacy generator can maintain a microgrid by leveraging the inverter with energy storage to support the load during the synchronization process. Since the inverter only needs to support the microgrid in small intervals, commercial scale inverters can be used, but at a higher rating. These inverters can be used with minor modifications in their switching algorithms and thermal design to meet the short term needs. The inverters are then smaller and cheaper. Figure 6 shows the proposed inverter integrated legacy generator. For a microgrid having a centralized control system, remotely located inverters can also be coordinated with the generators to provide grid support for synchronizing, load steps, etc. as discussed, offering significant flexibility and enhanced reliability. For this project's demonstration, a fully rated inverter will be used (reuse of an existing storage inverter to reduce project costs). Future installation can take advantage of lower rated inverters (a low risk technology).

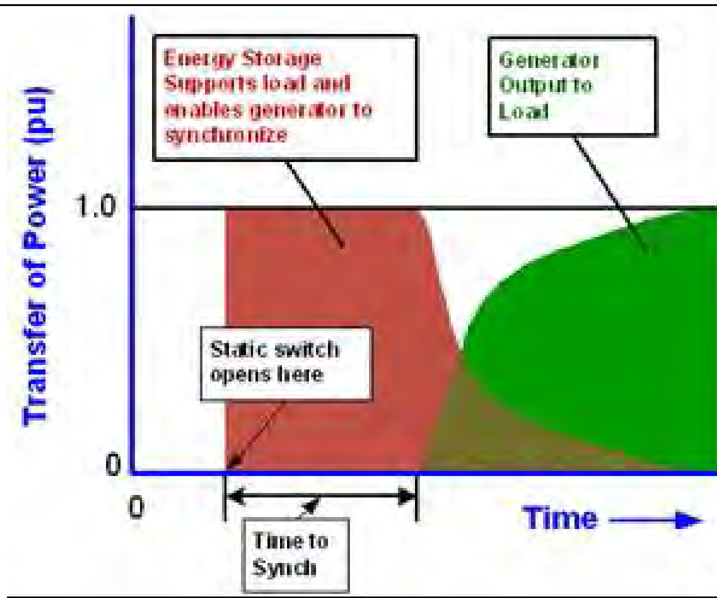

Figure 5: Inverter & Energy Storage Support to Legacy Generator

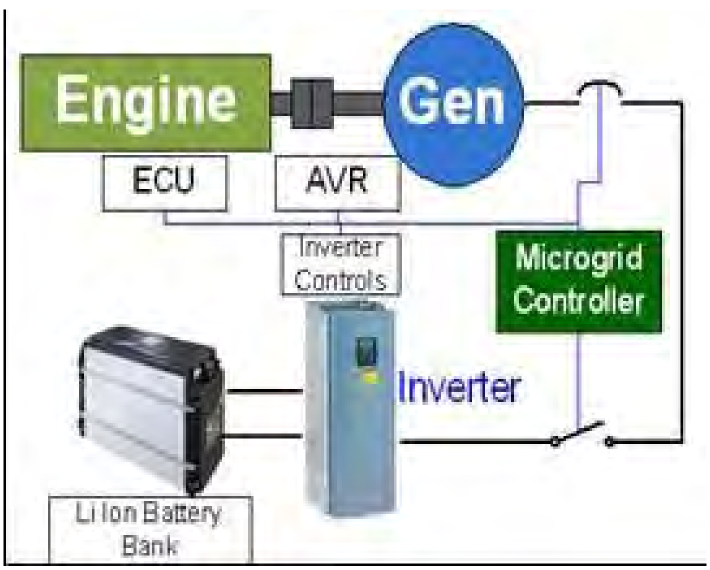

Figure 6: Inverter Integrated Generator

Power Optimized Energy Storage

The energy storage system implemented was a nano Lithium-Titanate Oxide (nLTO) system from Altairnano. This newer form of lithium-ion battery technology replaced the traditional graphite anode with a nanostructure Lithium-Titanate formula ($Li_4Ti_5O_{12}$). The cathode is Lithium Cobalt Nickel Manganese Oxide ($LiCo_xNi_yMn_zO_2$).

The complete battery system utilizing the nLTO cells is housed within two rack assemblies. Each rack assembly consists of two battery cabinets and an electronics cabinet that controls the power.

This system includes two strings of 20 (40 total) 24 V modules using 60 Ah cells wired in series. The system voltage is 360 V to 550 V.

Figure 7: One (of the two) battery rack assemblies at the Altairnano factory.

Comparison to Existing Technology

The Altairnano nLTO cell technology produces distinctive performance attributes, including extremely fast charge and discharge rates, the industry’s highest round-trip efficiencies, long cycle life, improved safety, and the ability to operate under diverse environmental and thermal conditions.

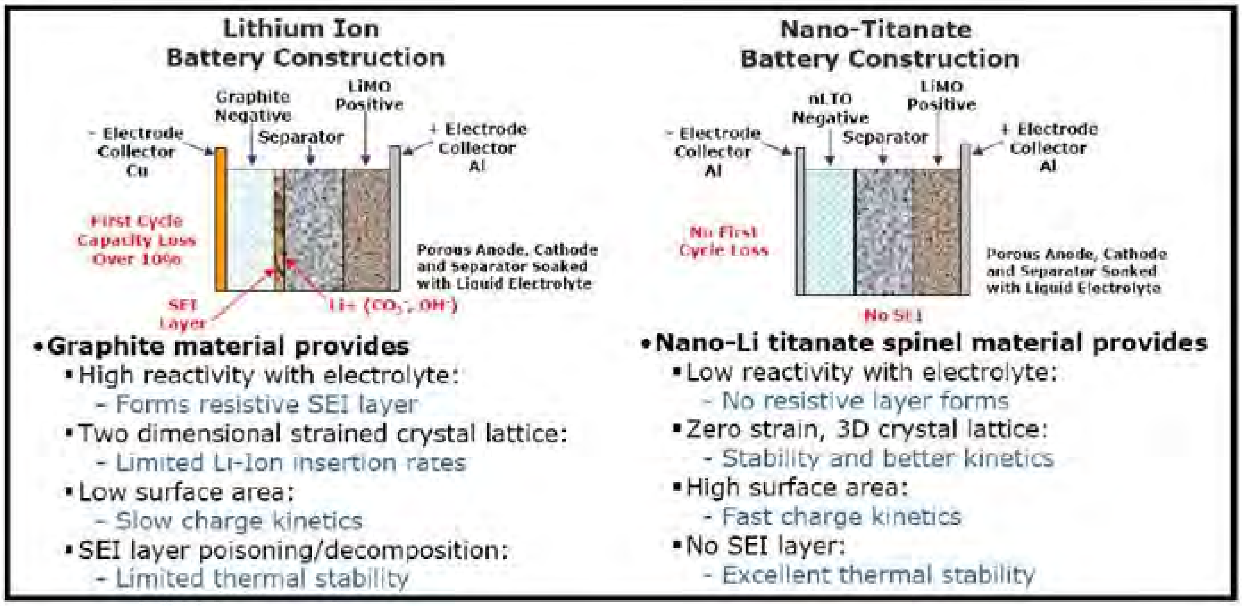

Figure 8: A comparison of traditional Li-ion structure with the nLTO structure.

The first benefit is the high power density. The nLTO structure has the ability to receive and discharge power at higher rates than any other lithium battery formulations without shortening the cycle life of the battery. While some Li-ion batteries can achieve a high discharge rate, they need to be recharged at slower rates. The nLTO has the ability to recharge as fast as it discharges, so that it can quickly be ready for the next time it is needed. Operating at high rates, the battery is capable of transitioning between full power charge and full power discharge in less than 100 μ seconds. The ESTCP application calls for charging and discharging cycles of 60 seconds each, and to repeat these cycles for as many as ten times in an hour.

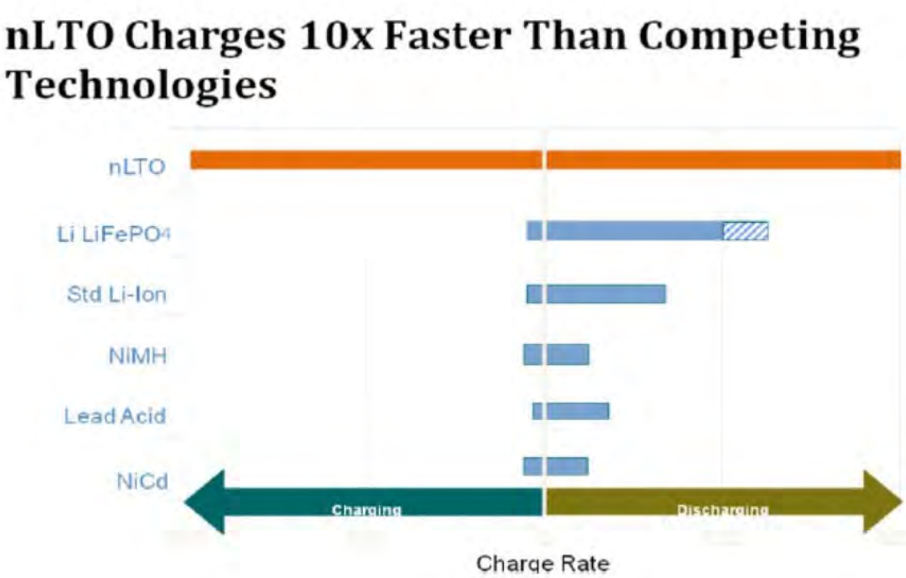

Figure 9: The nLTO battery system is capable of very high charging and discharging rates.

The energy density is also impressive. Unlike most other Li-ion batteries, the nLTO batteries can be fully discharged without degradation. This provides more usable energy from a given amount of battery mass than traditional Li-ion batteries. The traditional batteries cannot be discharged to less than 10% state-of-charge (SoC) without damage.

Even with the 100% discharge, these batteries can be cycled more than 16,000 times. The cells still retained over 80% of their original charge capacity at the end of these cycles. This cycle life is three to fifty times (3–50x) longer than other type of lithium batteries, and the calendar life is over ten times (10x) longer. This technology is well suited for long life applications.

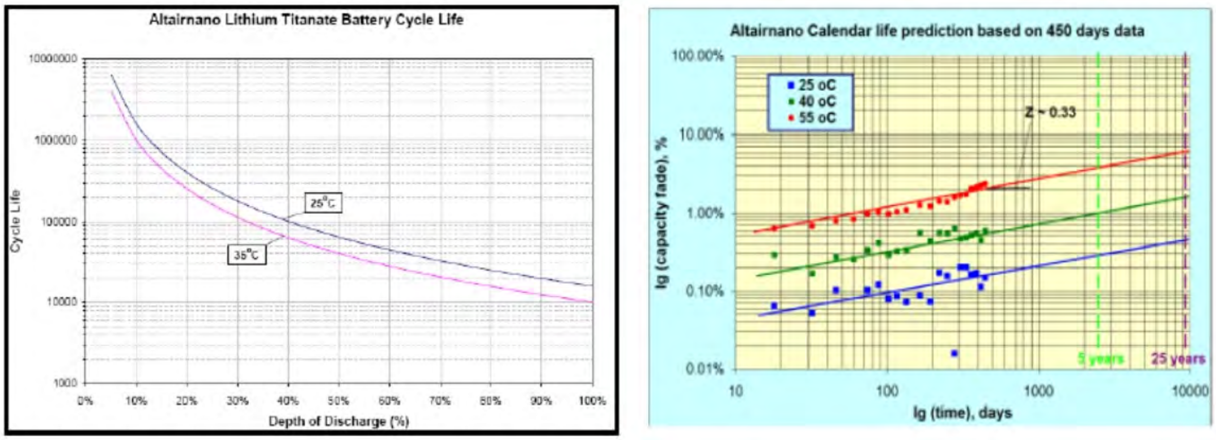

Figure 10: Cycle and calendar life degradation

The nLTO technology also represents a breakthrough in low and high temperature performance. Nearly 90% of room temperature charge retention is realized at -30°C due to the elimination of the solid electrolyte interface (SEI) layer found in all other lithium ion technologies. Other lithium ion technologies possess greatly reduced charging capabilities at temperatures below 0°C, and other, non-lithium ion rechargeable batteries take 10 to 20 times longer to charge at this low temperature. When operating batteries at low temperatures, loss of performance is a major concern.

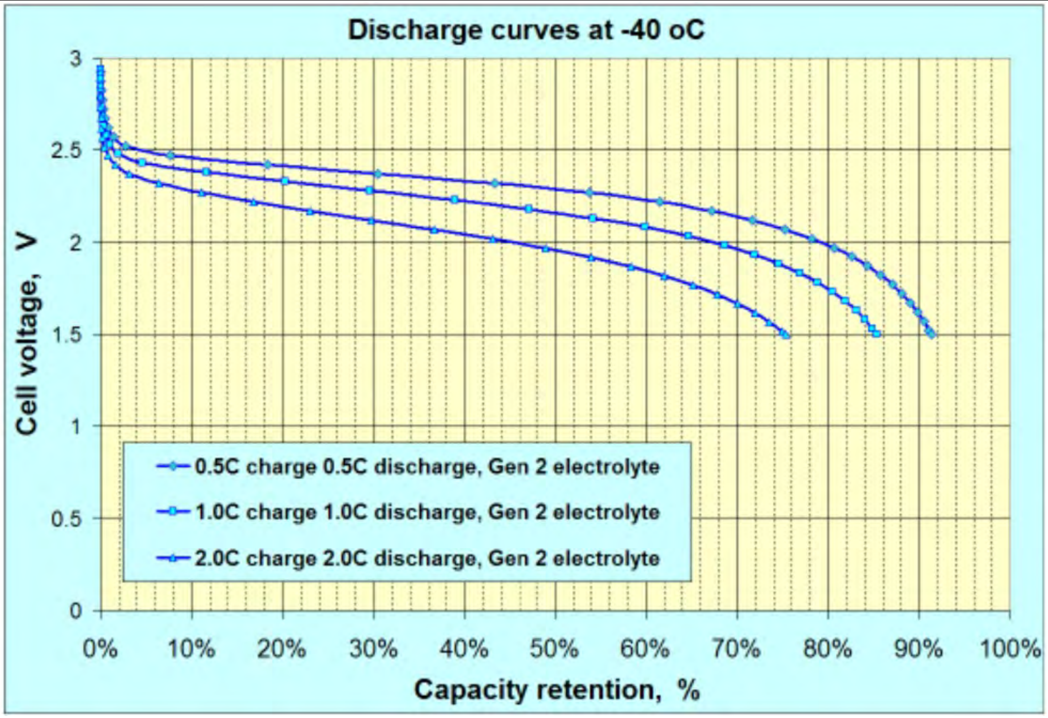

Figure 11: Discharge performance at -40°C

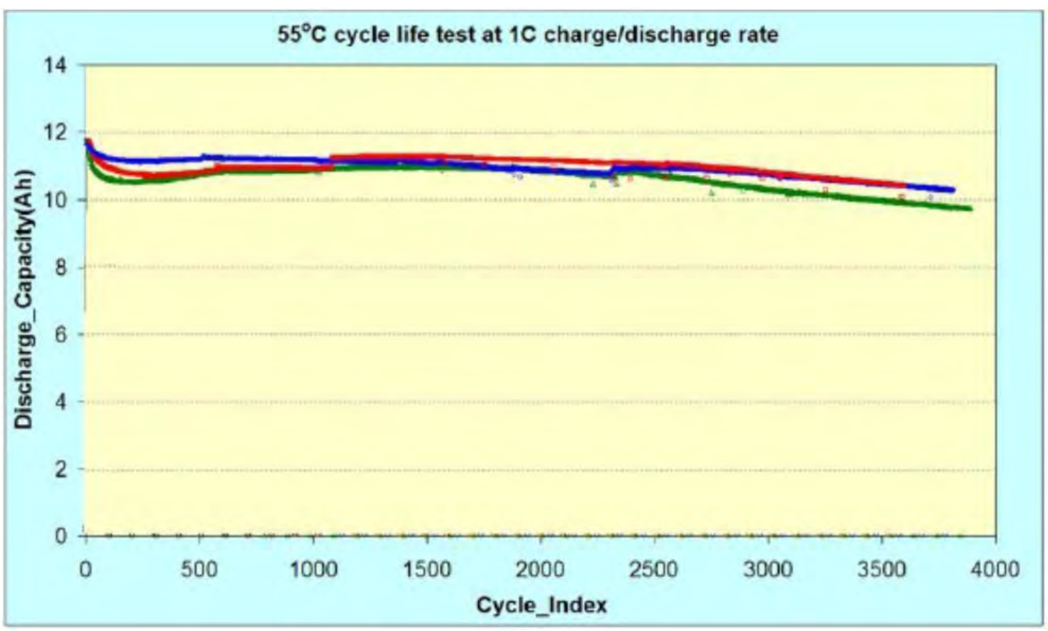

Figure 12: Discharge performance at 55°C

Lithium Titanate spinel used in Altairnano's nLTO is known to be safe up to temperatures of 250°C while graphite negative electrode materials used in other lithium ion batteries are known to suffer from thermal runaway issues at temperatures above 130°C. Altairnano has completed safety cycle testing subjecting cells to temperatures up to 240°C, more than 100°C above the temperature at which graphite-based batteries may exhibit thermal runaway.

Chronological Summary

The Altairnano technology is built upon proprietary advanced materials acquired from BHP Minerals International, Inc. in 1999. Altairnano continued to expand and refine various applications of the material technology. Today, the technology is used to produce various nano-sized powders, cells, and assembled battery modules that have current or potential applications within the energy sector.

Altairnano is currently working with electric utilities, industrial and transportation companies, and the US military in response to the issues seen within today's challenging energy markets. Today Altairnano is delivering product solutions, and advanced energy storage applications that include:

- Utility-scale and distributed grid energy storage systems (Ancillary Services, Grid Stability, etc.)
- Microgrids
- Renewable integration
- Military vehicles (sea, land, and air)
- Heavy-duty commercial vehicles (Buses, trains, ships, tow motors, etc.)
- Portable power for military applications

Altairnano has an 83,000 sq. ft. corporate headquarters and R&D facility in Reno, Nevada. It contains all equipment necessary to build and evaluate prototype battery cells. This includes mixing and coating equipment, a 600 sq. ft. dry room and several hundred channels of test equipment. Several environmental chambers are also used for defining thermal characteristics. The R&D facility also contains state-of-the-art electrochemical analysis equipment to study fundamental aspects of Altairnano battery technology. Manufacturing is performed at its plant in Anderson, Indiana. The facility contains a 1,650 sq. ft. dry room for cell manufacturing, and a wide array of battery test equipment including battery cyclers and environmental chambers.

Future Potential for DoD and Anecdotal Observation

Altairnano performed high-rate overcharge, puncture, crush, drop and other comparative tests in accordance with UN/DOT and Military 810 test procedures with no explosions or safety concerns exhibited by the nLTO cells.

Crane Division, Naval Surface Warfare Center (NSWC Crane) Test & Evaluation Branch (Code GXSM) was tasked by Altairnano to perform safety abuse testing on Lithium Nano-Scale Titanate Oxide Cells and Modules. Cell testing included overcharge testing, cell overheating, the investigation of thermal propagation between cells, and vent gas analysis of overcharged/overheated cells. Module testing included thermal propagation between cells, overcharge testing, overheat testing (via flame and/or heat tape), and determining the effectiveness of carbon dioxide, water, and FM200 in suppressing a Mark I module fire. The tests performed are improved or modified versions of test called out in NAVSEA TM-S9310 which are tests designed to provoke worst-case scenario responses from the cells/modules for preliminary assessment purposes and for identifying battery vulnerabilities. Detailed results are

reported in Crane Document Number: GDD GXS 11-053 (Preliminary Report) Issue Date: 05/3/2011.

PV Inverter with Microgrid Controls

Existing PV inverters with IEEE 1547 controls go offline on a utility outage or on a power quality event and will not support the microgrid. The control strategy used in the power storage inverter for converting legacy generators to microgrid compatible ones is applied to these PV inverters also. This will enable the PV energy source to be utilized in the microgrid as the prime source, to aid microgrid stability, and can further be integrated with the distributed power storage to address intermittent loss of PV energy as when a cloud passes over the PV array. This minimizes generator run time and offsets the required generator installed capacity (for islanding) based upon the PV electrical load carrying capacity.

2.2 TECHNOLOGY DEVELOPMENT

The bulk of the technology development was the integration of diverse equipment onto a microgrid capable control system. This system was based on an existing switchboard/generator control system (per CAT-ISO) with software modifications for storage inverter integration, and coordinated operation of sources. Modification of PV inverter for microgrid operation was also a software and integration effort. Descriptions and examples of this integration are given in Sections 4, 5 and 6.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Primary Benefits

The technology solution demonstrated provides a commercial path for converting existing distribution systems into microgrid capable systems without the high cost of grid scale energy storage. The solution achieves energy surety and security, high power quality, ride-through, fast-acting transient real and reactive power support and will enable islanding of microgrids. The power optimized energy storage and inverter used is commercial off-the-shelf technology and is approximately 33% of the cost of typical utility scale battery energy storage solutions deployed today. The storage inverter controls and hardware were leveraged to provide an islanding inverter (microgrid compatibility) for renewable energy sources (PV for this program), to maximize the effective load carrying capacity of the renewable energy source when grid connected or islanded.

Storage Technology Progression

While Li-ion batteries are the present, preferred choice (and planned for the demonstration), Eaton expects to ultimately transition to capacitor based storage for transient rated applications, as this technology is expected to become dominant for short duration high power applications as costs continue to decline. A key aspect to the Eaton power storage approach is that the short duration times enable an open architecture approach to storage technology, as both batteries and capacitors are possible, given the proper integrated system controls (that will be demonstrated).

While a battery based system was demonstrated, capacitor technologies are rapidly improving, with new products from established vendors (e.g. Maxwell), and new vendors (e.g. IOXUS) offering both ultracapacitors and Li-ion capacitors (sometimes called hybrid capacitors). A promising technology is the Prismatic Ultracapacitor series from IOXUS. The advantages of these Li-ion based capacitors include high operating temperature range (-40V to +65C), high cycle life (500,000), long lifetime (10 years), and environmental friendliness. They are optimized for high power (i.e. high current) applications, and can be rapidly charged as well as discharged.

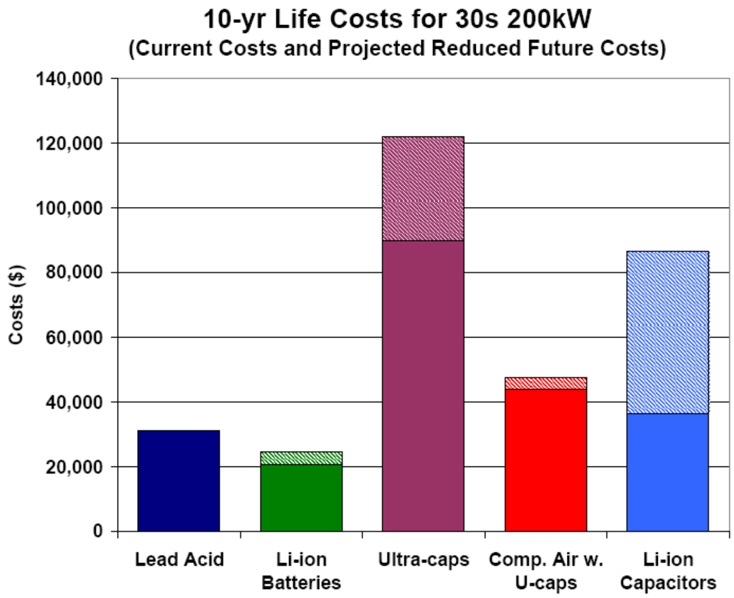

Figure 13: Ten year Life Costs for 30s 200kW

Reduced Ability to Perform Load Shifting

A primary focus of this project was to demonstrate a reduction in energy storage (and its cost) while maintaining power surety. The available storage was used to support generator transitions, and leveling of renewable power steps (e.g. cloud passing) in order to maintain power quality within the microgrid. As such, load shifting (storing excess renewable energy for time shifted use when renewable power is not available) did not occur to a significant extent using the power optimized batteries (for this project). Instead the bulk of the renewable energy will immediately be consumed (within the microgrid) or exported to the utility. For the islanded microgrid case, the natural gas generators were used to provide power. The proposed power optimized storage concept is not incompatible with load shifting, but it is not optimized for it. Cost reduction while maintaining power surety was the optimization target for this project.

This approach (immediately consuming renewables, and using generators as needed when islanded) can be shown to be a more cost effective method than time shifting the renewable energy. The payback time for time shifting is very long given the high cost of bulk energy storage, and low cost of utility power. For example, the energy optimized ZBB system can store

500kWHr of PV energy for use at night. Assuming an energy cost of $0.12 / kWHr, the result is $60 of energy per night. Given the cost of the ZBB system, the payback time is 27 years.

High Inrush Loads

As the primary large load on the microgrid, the chiller induction motor presented operational challenges as it was a very high inrush current load on startup, since it used a Wye-Delta starter. Replacing that starter with a soft starter or variable speed drive would have reduced the peak currents and improved chiller start operation when islanded. Unfortunately, starter replacement was not an option at this site (no permission to change chiller load system). In future installations, optimizing the control of motor loads is recommended.

Generator Run Time

At the Fort Sill site, restrictions on generator run time limited the duration of islanded operation and hence microgrid effectiveness. While the power optimized storage technical approach is sound, it does require the ability to run generators as needed for islanded operation. Treating the generators as emergency backup class devices was a limitation on microgrid effectiveness.

3 PERFORMANCE OBJECTIVES

This section describes the technology and economic Performance Objectives (PO) that were successfully demonstrated. These objectives will show the contribution of this technology to DoD Energy and Water goals for Energy Security and Cost Avoidance for military installations.

- Energy and Water Security: The demonstration performance objectives show that power optimized storage is suitable for military microgrid applications in terms of stabilizing the islanded microgrid bus voltage, supporting loads, and enabling faster generator synchronization. The objectives will also show that high penetration PV can be enabled to support islanded microgrid buses and variable loads.
- Cost Avoidance: The demonstration performance objectives show that power optimized storage is suitable for military microgrid applications, and that such storage systems have a significantly lower procurement cost than typical energy optimized storage systems used in utility and microgrids installations.
- Greenhouse Gas Reduction: Not applicable for this demonstration project.

3.1 "TABLE 1" SUMMARY OF PERFORMANCE OBJECTIVES

The Eaton team collected data during system operation to evaluate the technical objectives of the project. A summary of proposed performance objectives is provided in Table 1 below. These performance objectives are in alignment with the tasks and activities described in the original project proposal and resulting contract awarded.

Performance Objective	Metric	Data Requirements	Success Criteria
Table 1: Performance Objectives **Quantitative Performance Objectives**			
Demonstration 1 Load support with rapid generator synchronization	Seconds	Microgrid voltage and frequency measurement. Generator, storage inverter output power measurements. Load power measurements.	Synchronization of both generators with no loss of microgrid loads.
Demonstration 2 Load step support to recover voltage and frequency	kW, kVARs, Volts, Hertz, Seconds	Microgrid voltage and frequency measurement and time to recover from a step load.	Load step voltage and frequency recovery improved by 50%. Comparing case with and without storage system.

Demonstration 3 Storage powering of microgrid without generators	kW, kVARs, Volts, Hertz	Load voltage and frequency measurement.	>45 seconds of islanded microgrid power without loss of power quality to loads (60% of storage rated power). Power quality (PQ) defined as voltage maintained within +10%/-12%, and frequency within 60.3Hz/59.3Hz.
Demonstration 4 Quantify fuel savings given PV for islanded operation	Natural gas fuel use (ft^3)	Estimated fuel consumption as derived from generator run time and load level	Actual field data that quantifies fuel savings given high penetration PV. Condition 1: Running operation without PV. Condition 2: with PV active.
Demonstration 5 PV + Storage support managing variable loads	kW, kVARs, Volts, Hertz	Microgrid voltage and frequency measurement. Microgrid load power measurements. PV system output power measurement.	Load step of 50% of available PV with stable microgrid bus, with no generators on line and above 30% PV rated power available. Stable bus is defined as voltage maintained within +10%/-12%, and frequency within 60.3Hz/59.3Hz.
Demonstration 6 PV + Storage support managing variable solar	kW, kVARs, Volts, Hertz	Microgrid voltage and frequency measurement. Microgrid load power measurements. PV system output power measurement.	In a solar day with the load less than 50% of average available PV, microgrid bus will remain stable, with no generators on line. Stable bus is defined as voltage maintained within +10%/-12%, and frequency within 60.3Hz/59.3Hz.

Demonstration 7 Procurement cost reduction of storage	$	Production costs of storage systems	67% reduction of procurement cost of storage system
Demonstration 8 Smaller footprint for storage	$Feet^2$ (area)	Floor space required for storage systems	50% reduction of storage system footprint
Demonstration 9 Ramp rate control of PV power transitions with support from energy storage	kW, kVARs, Volts, Hertz, seconds	Microgrid voltage and frequency measurement. Microgrid load power measurements. PV dc power measurement. Storage inverter output measurement.	60 second effective ramp down of power given PV reduction (due to cloud passing overhead). With and without ramp rate control enabled, typical solar days.
Demonstration 10 High penetration PV and control of PV power ramp rate for generator stability	kW, kVARs, Volts, Hertz, seconds	Microgrid voltage and frequency measurement. Microgrid load power measurements. PV dc power measurement, storage inverter and generator output measurement,	Generator output voltage stability given a 60% PV DC power step (up or down). Stability is defined as voltage maintained within +10%/-12%, and frequency within 60.3Hz/59.3Hz.
Demonstration 11 Microgrid voltage support from PV inverter	kVARs, Volts, seconds	Microgrid voltage measurement. Microgrid load kVAR measurements. PV inverter kVAR measurements.	125 kVAR contribution by PV inverter during a reactive load step. (i.e. islanded chiller load start or a load bank).

Demonstration 12 Validate/Quantify storage needs – peak power and time duration	Power output and cycle count	Storage system power output profile (Peak Power and time duration) over extended operating period	Actual field data that quantifies storage need based on microgrid capacity. Condition 1: 1 month of free running operation. (Note: Storage system will be supporting chiller starts - the primary large load). Condition 2: 1 month with an added variable load (using IAPS system) that emulates the worst case load profile seen during condition 1.
Demonstration 13 Assessment of application areas within DoD infrastructure	DoD Sites, MW	DoD site power system data, power (profile) needs, and energy security requirements	50 MW of potential DoD application areas identified having strategic mission significance

3.2 PERFORMANCE OBJECTIVES DESCRIPTIONS

A summary of each performance objective listed in Table 1 is described below. Demonstration results are discussed in Section 6.

Demonstration 1: Load support with rapid generator synchronization.

- Purpose: This demonstration shows that power optimized storage is able to stabilize the microgrid voltage and frequency during a load step, thus enabling a rapid synchronization of generators onto the microgrid from an initially off state.
- Metric: Time measurement in seconds.
- Without stabilization provided by the power optimized storage system, the unstable microgrid voltage and frequency results in longer times for generator synchronization, and sequential synchronization of multiple generators, taking over 60 seconds.
- Data: Microgrid voltage and frequency measurements. Generator and storage inverter output power measurements. Load power measurements.
- Analytical Methodology: Eaton will use a tabular summary of test results to show the synchronization time.

- Success Criteria: Synchronization of both generators within 30 seconds. No loss of microgrid loads due to lack of available power or microgrid voltage and frequency oscillations.

Demonstration 2: Load step support to recover voltage and frequency.

- Purpose: This demonstration shows that power optimized storage is able to support the microgrid voltage and frequency during a load step, thus reducing the time required for the voltage and frequency to stabilize.
- Metric: kW, kVARs, Volts, Hertz, Seconds.
- Without support provided by the power optimized storage system, the load step will cause microgrid voltage and frequency oscillations of long duration, potentially causing loads to trip off.
- Data: Microgrid voltage and frequency measurement and time to recover from a step load.
- Analytical Methodology: Eaton will use a tabular summary of test results to show the voltage and frequency recovery comparison.
- Success Criteria: Load step voltage and frequency recovery improved by 50%. Comparing case with and without storage system.

Demonstration 3: Storage powering of microgrid without generators.

- Purpose: Demonstrate the ability of the power optimized storage system to support the microgrid alone (without generators) during a grid outage or equivalent event.
- Metric: kW, kVARs, Volts, Hertz.
- The majority of grid outages are brief events, lasting a few seconds or tens of seconds. A storage system that provides grid support for this brief time, and not for hours, is a cost effective system solution. Generators (and/or renewables) can be used for long duration outages more cost effectively than high capacity energy storage.
- Data: Load voltage and frequency measurement.
- Analytical Methodology: Eaton will use a tabular summary of test results to show the power quality (voltage and frequency) being maintained during the islanded time (under storage power).
- Success Criteria: Greater than 45 seconds of islanded microgrid power without loss of power quality to loads (60% of storage rated power). Power quality (PQ) defined as voltage maintained within +10%/-12%, and frequency within 60.3Hz/59.3Hz. These limits are those specified in IEEE 1547 for interconnection of distributed resources. (The voltage and frequency excursions will be less than these limits).

Demonstration 4: Quantify fuel savings given PV for islanded operation.

- Purpose: This effort will quantify the fuel savings provided by high penetration PV in a microgrid where generators are primary sources when islanded.
- Metric: Natural gas fuel use (ft^3).
- High penetration PV can offset generator fuel use for an islanded microgrid. The reduction in fuel results in either lower power demand from operating generators, or

generators not running. This test effort will be constrained by generator run time restrictions at Fort Sill.

- Data: Estimate of fuel consumption derived from generator run time and load level.
- Analytical Methodology: Eaton will use a tabular summary of test results to show the generator run time, load level, and estimated fuel use over the test period.
- Success Criteria: Actual field data that quantifies fuel savings given high penetration PV.
  - Condition 1: 1 month of free running operation without PV.
  - Condition 2: 1 month with PV active. Actual allowed generator run time may be limited due to site restrictions and conditions.
  - In this event, data will be extrapolated to quantify monthly fuel savings.

***Demonstration 5: PV + Storage support managing variable loads*.**

- Purpose: Demonstrate the ability of microgrid compatible PV with storage support to manage variable loads while islanded, without generators online.
- Metric: kW, kVARs, Volts, Hertz.
- Typical PV inverters go offline when the utility is not present. A PV inverter, combined with storage inverter support and microgrid controls, can power a microgrid without generators, given power demand within the PV available output capacity.
- Data: Microgrid voltage and frequency measurement. Microgrid load power measurements. PV system output power measurement.
- Analytical Methodology: Eaton will use a tabular summary of test results to show the voltage, frequency being sourced by PV and storage alone.
- Success Criteria: Load step of 50% of available PV with stable microgrid bus, with no generators on line and above 30% PV rated power available. Stable bus is defined as voltage maintained within +10%/-12%, and frequency within 60.3Hz/59.3Hz.

Demonstration 6: PV + Storage support managing variable solar.

- Purpose: Demonstrate the ability of microgrid compatible PV with storage support to manage variable solar (available power) while islanded, without generators online.
- Metric: kW, kVARs, Volts, Hertz.
- Typical PV inverters go offline when the utility is not present. A PV inverter, combined with storage inverter support and microgrid controls, can power a microgrid without generators, given variable PV power and power demand within the PV available output capacity.
- Data: Microgrid voltage and frequency measurement. Microgrid load power measurements. PV system output power measurement.
- Analytical Methodology: Eaton will use a tabular and graphical summary of test results to show the voltage, frequency being sourced by PV and storage alone over an extended time period (a typical solar day).
- Success Criteria: In a solar day with the load less than 50% of average available PV, microgrid bus will remain stable, with no generators on line. Stable bus is defined as voltage maintained within +10%/-12%, and frequency within 60.3Hz/59.3Hz. The 50% level is selected based on power (and not energy) optimized battery.

Demonstration 7: Procurement cost reduction of storage.

- Purpose: Demonstrate that a significant equipment cost reduction can be achieved by using power optimized storage.
- Metric: Cost in US dollars ($).
- Storage system costs are typically the largest cost item for a military microgrid. A reduced procurement cost enables wider acceptance and use of microgrids for DoD installations.
- Data: Procurement costs for storage systems.
- Analytical Methodology: Table comparing equipment costs.
- Success Criteria: A 67% reduction of procurement cost of storage system for the new power optimized storage versus the existing energy based storage system (flow battery) at the Fort Sill microgrid.

Demonstration 8: Smaller footprint for storage.

- Purpose: Having a smaller equipment footprint benefits the site by allowing for more flexibility in installation location selection, including indoors, lower installation costs, and enabling simpler portability (if needed).
- Metric: Footprint area of storage system in $feet^2$.
- Common energy based storage systems typically require a large installation space, whereas a power optimized storage system is more compact.
- Data: Floor space required for storage systems.
- Analytical Methodology: Table comparing footprint areas.
- Success Criteria: A 50% reduction of storage system footprint for the new power optimized storage versus the existing energy based storage system (flow battery) at the Fort Sill microgrid.

Demonstration 9: Ramp rate control of PV power transitions with support from energy storage.

- Purpose: Demonstrate the ability of the combined PV and storage to ramp the "effective" power down during a PV power reduction event (i.e. a cloud passing overhead).
- Metric: kW, kVARs, Volts, Hertz, seconds.
- A rapid PV power reduction event can cause grid instabilities when the PV is a high penetration of local power. By using storage to reduce power over a longer time (effectively ramping it down), the utility supply is able to respond more effectively to the loss of PV power.
- Data: Microgrid voltage and frequency measurement. Microgrid load power measurements. PV dc power measurement. Storage inverter output measurement.
- Analytical Methodology: Eaton will use a graphical summary of test results to show the PV and storage power during the ramp down period.
- Success Criteria: 60 second effective ramp down of power given PV reduction (due to cloud passing overhead). With and without ramp rate control enabled, collect data over typical solar days.

Demonstration 10: High penetration PV and control of PV power ramp rate for generator stability.

- Purpose: Demonstrate the ability of the storage system to maintain a stable islanded microgrid bus during PV power steps (by ramping total power), when islanded with generators and PV sources.
- Metric: kW, kVARs, Volts, Hertz, seconds.
- A solar irradiation step can result in microgrid instabilities, given generator and high penetration PV sources (approximately 18% in this microgrid). By using storage to ramp power (up or down to the final value as needed) over a longer time, the generator output is stabilized resulting in a stable microgrid bus.
- Data: Microgrid voltage and frequency measurement. PV DC power measurement, storage inverter and generator output measurement.
- Analytical Methodology: Eaton will use a graphical summary of test results to show the storage inverter power ramping, and microgrid bus voltage stability during the load steps.
- Success Criteria: Generator output voltage stability given a 60% PV DC power step (up or down). Stability is defined as voltage maintained within +10%/-12%, and frequency within 60.3Hz/59.3Hz.

***Demonstration 11: Microgrid voltage support from PV inverter*.**

- Purpose: The PV inverter can supply kVARs to support microgrid voltage during load steps independent of the PV power available.
- Metric: kVARs, volts, seconds.
- During typical usage the full kVA capacity of PV inverters is not utilized for delivering PV power (as solar illumination may be limited). Typically 50% of the capacity is available. This inverter capacity can be used for grid support, given integration with the microgrid control system.
- Data: Microgrid voltage measurement. Microgrid load kVAR measurements, PV inverter kVAR measurements.
- Analytical Methodology: Eaton will use a tabular summary of test results to show the kVAR contribution of the PV inverter during load steps.
- Success Criteria: A 125 kVAR contribution by PV inverter during a reactive load step. (i.e. islanded chiller load start or a load bank). This is 50% of the kVA capacity of the PV inverter.

Demonstration 12: Validate/Quantify storage needs – peak power and time duration.

- Purpose: Obtain actual field data to validate/quantify the required ratings for power optimized storage. Peak power demand, pulse time, and number of cycles will be measured over an extended operating period.
- Metric: Power output and cycle count.
- The key cost driver for power optimized storage is peak power demand and pulse time (duration). An accurate assessment of the storage need based upon the microgrid rating provides a means for determining minimized storage costs for microgrids having different ratings and characteristics.

- Data: Storage system power output profile (Peak Power and time duration) over extended operating period.
- Analytical Methodology: Eaton will use a tabular summary of test results to show the power versus time for the cycles encountered over the test period.
- Success Criteria: Actual field data that quantifies storage need based on microgrid capacity.
    - Condition 1: 1 month of free running operation. (Note: Storage system will be supporting chiller starts - the primary large load).
    - Condition 2: 1 month with an added variable load (using IAPS system) that emulates the worst case load profile seen during condition 1.
    - These two conditions enable characterization of the typical and maximum severity of pulse power needs.

Demonstration 13: Assessment of application areas within DoD infrastructure.

- Purpose: Identify DoD sites that could benefit from microgrids with power optimized storage, and their potential microgrid power needs for strategic missions.
- Metric: DoD facility application sites, MW power usage.
- Many DoD sites could benefit from cost effective microgrids. This assessment will be an initial estimate of the potential DoD market for microgrids with power optimized storage. These would be facilities with significant existing on site generation and/or renewables.
- Data: Power system ratings, power profile needs, and energy security requirements for a number of potential DoD microgrid sites.
- Analytical Methodology: A tabular listing of potential DoD microgrid sites, their total power system capacity, and an estimate of microgrid suitable power rating of a portion of those power systems, and identification of their strategic mission significance. (This analysis will be done in conjunction with CERL personnel).
- Success Criteria: 50 MW of potential DoD microgrid application areas identified that have strategic mission significance.

4 FACILITY/SITE DESCRIPTION

Fort Sill weather is typical of the southwest with high summer temperatures and the potential for low winter temperatures. It is also in the path of severe storms during spring and early summer. These conditions made for a good location to test the ability of microgrid equipment to operate in the climate extremes and for this equipment to provide energy surety during severe weather conditions.

The Fort Sill Military base is located in the southwestern region of Oklahoma, approximately 80 miles (130 km) southwest of Oklahoma City (shown in Figure 14). Fort Sill lies in an area that is typical of the Great Plains with prairie, few trees, and flat topography with gently rolling hills. The region north of the city consists of the Wichita Mountains. Fort Sill lies in a dry subtropical climate, with frequent variations in weather daily, except during the constantly hot and dry summer months. Frequent strong winds, usually from the south or south-southeast during the summer, help to lessen the hotter weather. Northerly winds during the winter can occasionally intensify cold periods. The average mean temperature for the southwest Oklahoma is 61.9 °F (16.6 °C). The summers can be extremely hot; Lawton averages 21 days with temperatures 100 °F (37.8 °C) and above. The winter months are typically mild, though there can be periods of extreme cold. Lawton averages eight days that fail to rise above freezing. The city receives about 31.6 inches (800 mm) of precipitation and less than 3 inches (80 mm) of snow annually. Fort Sill is located squarely in area known as Tornado Alley and is prone to severe weather in late April through early June.

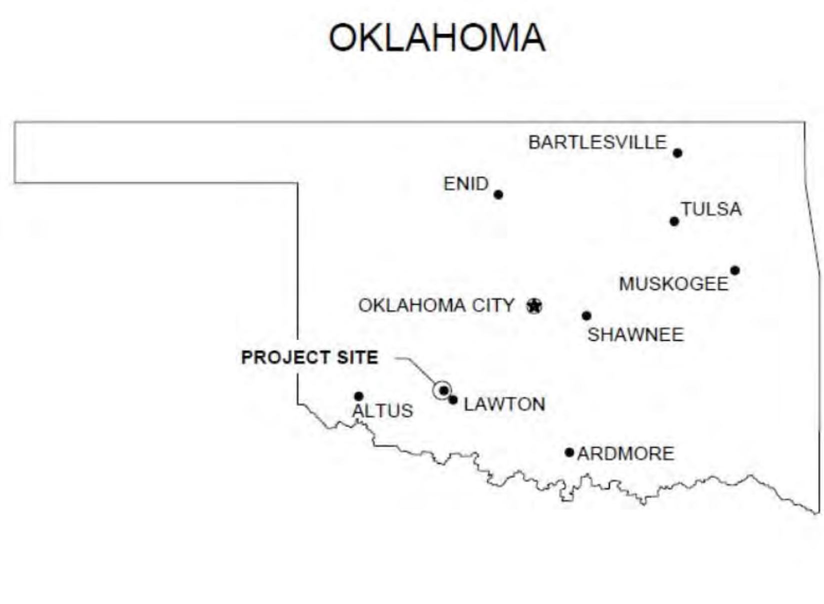

Figure 14: Project Site at Fort Sill, Oklahoma

Facility Criteria

This project involved the Central Energy Plant (CEP) Building 5900 that is located on Francis Street at Fort Sill, Oklahoma (see Figure 15). The terrain in and around building 5900 is basically flat with a few selected areas south of building 5900 that are used for runoff water retention (see Figure 16). The terrain does not measurably impact the demonstration other than the mounting system for an associated PV array is established to be above the understood maximum water line. The CEP provides the cooling needs of the five Starship training buildings in the vicinity. It is a specific chiller (designated as #3) in this overall CEP cooling system that is included in the microgrid central to this demonstration. The operation of this chiller will allow the critical systems of one or more Starships to be operable during utility power outages.

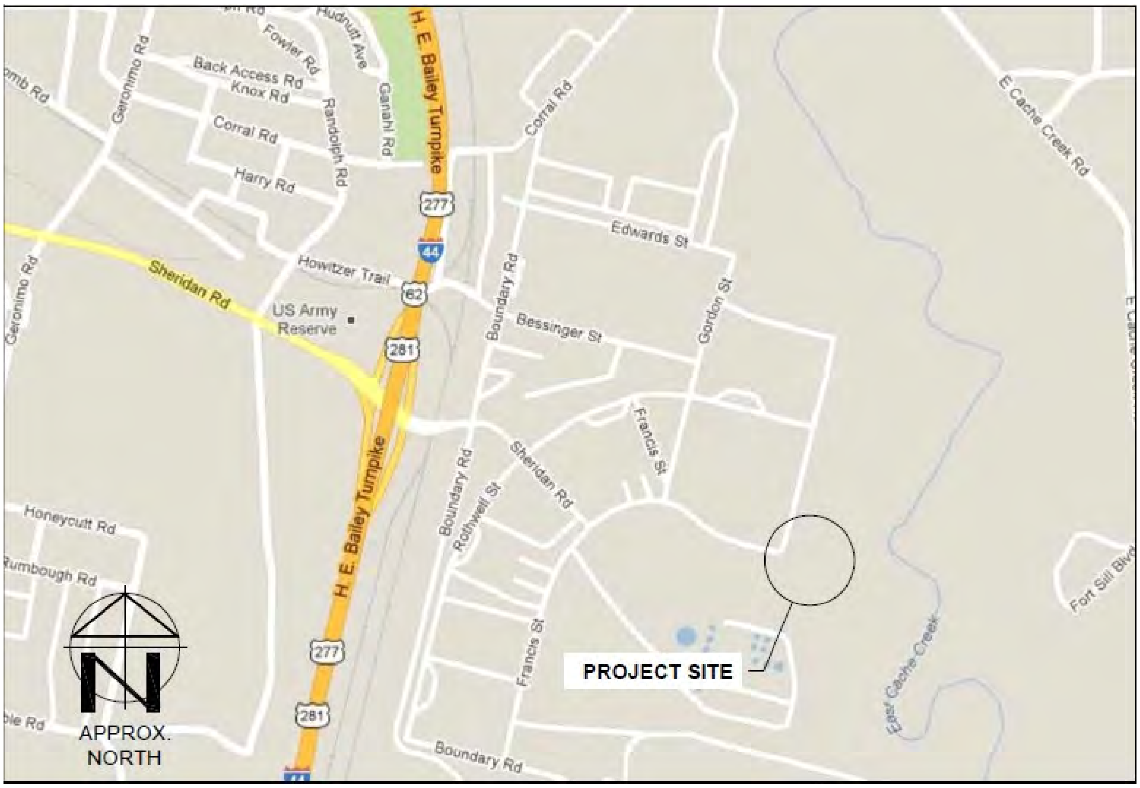

Figure 15: Project Street Location

Figure 16: Aerial View of Building 5900 and Local Terrain

Facility Representativeness

The microgrid demonstration was specified and designed to be a small (~400kW) representative example of future energy surety installations. Building 5900 and the chiller loads represent a broad based representative example for a number of reasons including:

- The CEP cooling system operation is considered essential to the continuation of the Starship training activities.
- The operation of the chiller system represents a particularly difficult load to start and manage; therefore it represents a “worst case” test for the microgrid system.
- The microgrid system integrates a wider variety of distributed generation sources, including natural gas generators, solar PV installations, Wind installation, and an energy storage system.
- Building 5900, the CEP cooing system are part of a larger and longer term vision of being able to island all the substation feeder that they are part of. This project can be seen as a one of the first steps in achieving this vision.

Given the high power loads included in this demonstration and how it is incorporated into the larger power system of Central Energy Plant (CEP) Building 5900 and how this system fits into the larger ‘feeder based’ microgrid plans for Fort Sill, it will be possible to replicate and expand upon this technical work and overall design at virtually any military base.

Other Selection Criteria

No other criteria are identified.

4.1 FACILITY/SITE LOCATION AND OPERATIONS

- Demonstration Site Descriptions
  Fort Sill is a United States Army post in Lawton, Oklahoma, about 85 miles southwest of Oklahoma City.

- Key Operations
  Today, Fort Sill remains the only active Army installation of all the forts on the Southern Plains built during the Indian Wars. It is designated as a National Historic Landmark and serves as home of the United States Army Field Artillery School as well as the Marine Corps' site for Field Artillery MOS School, United States Army Air Defense Artillery School, the 31st Air Defense Artillery Brigade, the 75th Fires Brigade and the 214th Fires Brigade. Fort Sill is also one of the five locations for Army Basic Combat Training. The 5 Starship training facilities that are provided cooling water from the Central Energy Plant (CEP) Building 5900 are central to meeting the training mission of this military base.

- Command Support
  Fort Sill supports the Eaton/ESTCP demonstration on the DoD facility. The POC for the Ft. Sill facility was Mr. Christopher Brown, Energy Manager. Fort Sill provided a letter of support which was submitted at the proposal stage of this program and he continued to stay closely connected with the microgrid projects. Chris Brown's contact information can be found in Appendix B. Note: Chris Brown recently transferred to Fort Riley Kansas. Mr. Brown's Fort Sill replacement is Kevin Jackson.

- Communications
  The information security / DIACAP plan for previous microgrid projects has been to integrate the necessary communications and control functionality on the already DIACAP certified Trane system at Fort Sill. Essentially, the functionality is simply piggy-backing onto the Trane system and not creating any new communication paths. This is similar to the process followed when additional HVAC nodes are added to the Starships and other buildings; these extensions of the DIACAP certification have not been difficult. This effort was completed with the cooperation of Trane. No new certification was required, as the current chiller system has been certified a few times by Trane previously.

- Location / Site Map
  The location of the original microgrid demonstration hardware is shown in Figure 17. This project expanded this system by adding more PV, and replacing the existing batteries with a power optimized battery system. The location of the new PV array and PV inverter is shown in Figure 18. The location inside building 5900 of the new battery system and relocated storage inverter is shown in Figure 19.

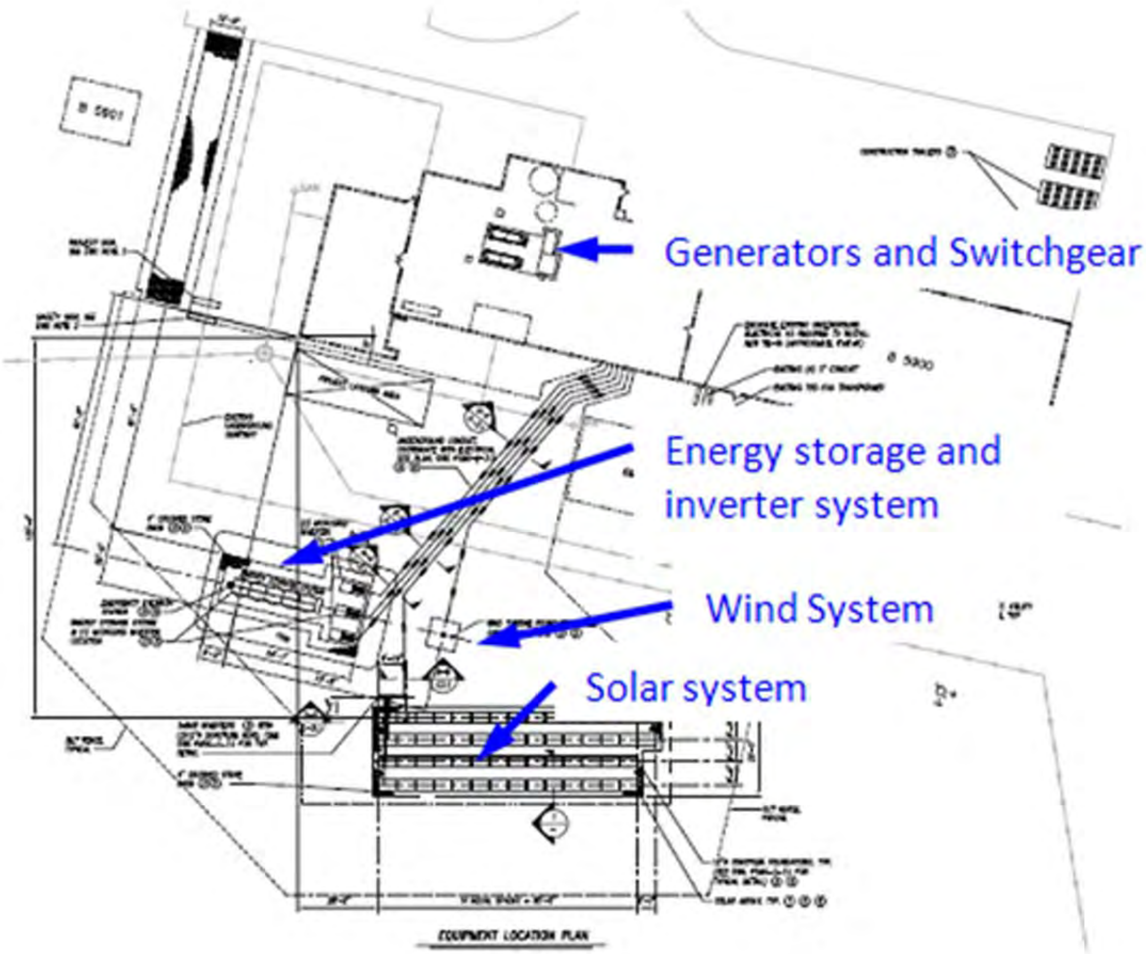

Figure 17: Original Fort Sill Microgrid Demonstration Hardware

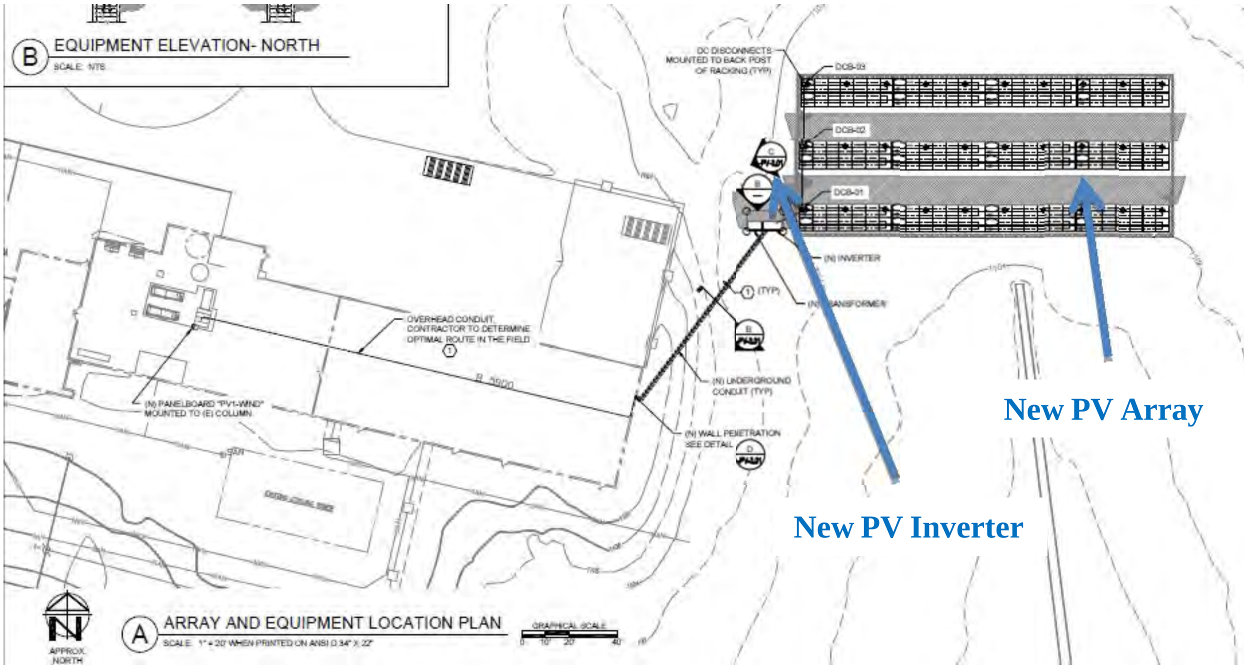

Figure 18: New PV Array and PV Inverter Location

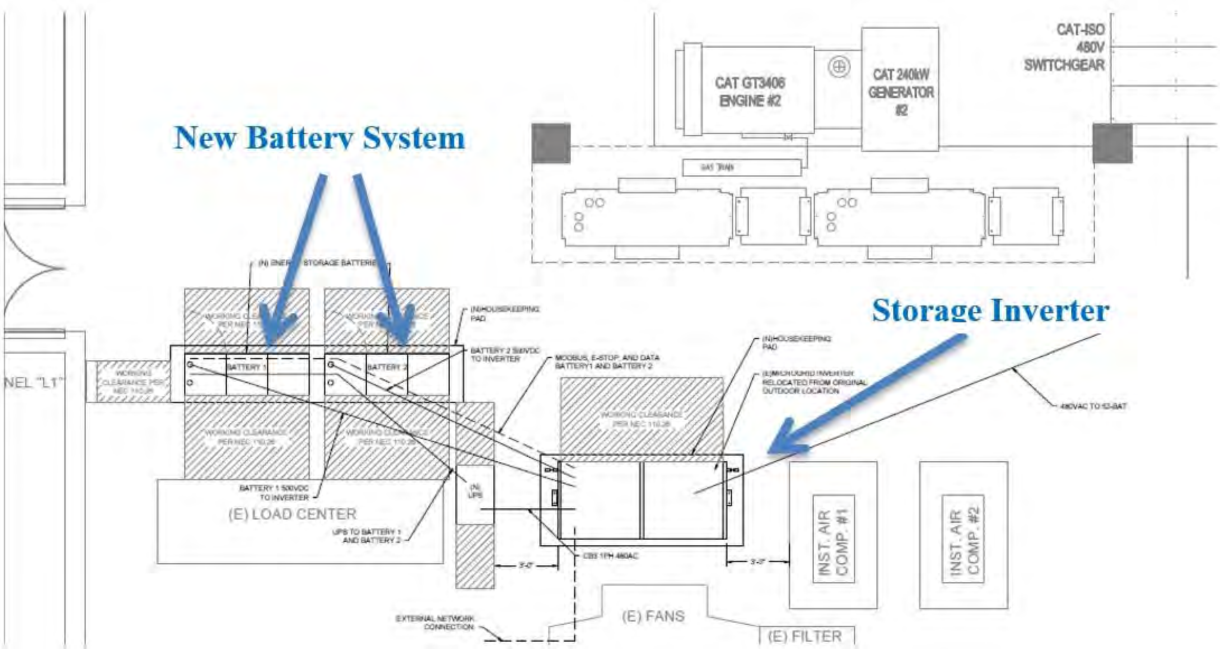

Figure 19: Storage Inverter and Batteries located Building 5900

A one-line diagram of the microgrid is shown in Figure 20. The items in red are changes, with blue items being added by this project to the existing microgrid.

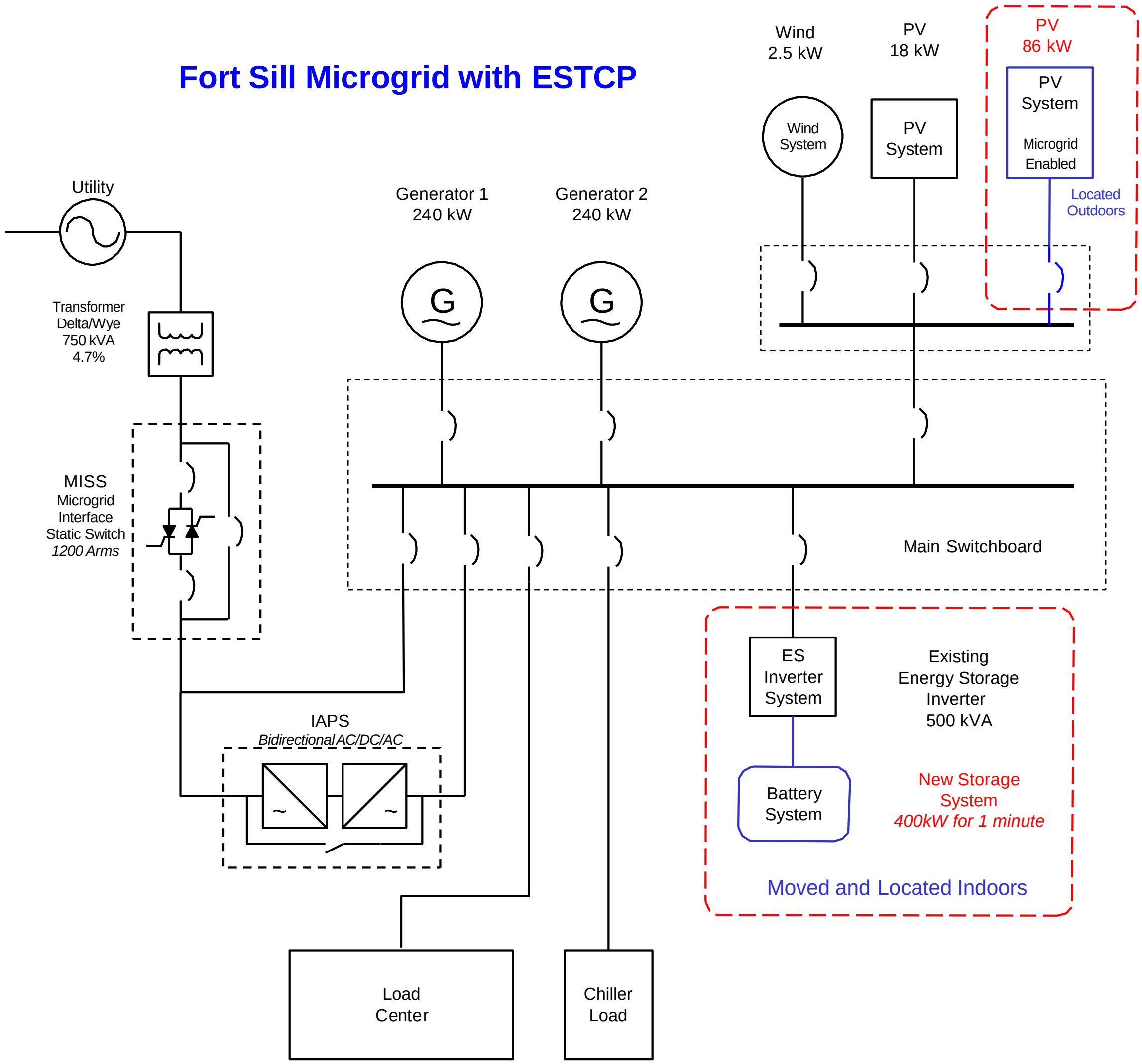

Figure 20: Fort Sill Microgrid with ESTCP Project Additions

- <u>Other Concerns:</u>
  No other concerns are identified.

4.2 FACILITY/SITE CONDITIONS

Site conditions are described above.

5 TEST DESIGN

This section provides a description of the system design and testing procedure to address the performance objectives described in Section 3.0. While many items are being demonstrated, they are all part of the primary problems and questions being addressed by the demonstration tests, which are the following:

- Fundamental Problem: Natural gas powered backup generators take more time to synchronize and connect to an existing off-grid system (microgrid), resulting in poor power quality during transient events when added generation is needed.

  Energy storage is a high cost element in microgrids, and limits the expansion of microgrids to new installations.

  Use of renewables like PV is recognized as necessary for long term energy surety and managing loads off-grid without natural gas generators is important when the energy from the PV fluctuates.

- Demonstration Question: The demonstration addresses the question: "can a short-time energy storage with high power rating stabilize the microgrid and reduce the time to synchronize and not oversize the generator?"

  The demonstration addresses the capability of lower cost power optimized storage to provide the needed power support for microgrids.

  The demonstration addresses the capability of the proposed system to operate off-grid and without the natural gas engines with PV and energy storage as the only sources.

5.1 CONCEPTUAL TEST DESIGN

- Independent variable: The primary independent variables are the response of the storage system (in kW and kVAR), the availability of the generators (on or off line), the load steps events (given the various scenarios described in section 3), and the kVAR output of the PV inverter.

- Dependent variable(s): The primary dependent variables are the microgrid voltage and frequency (relative to power quality), the available PV power (given weather conditions), the generator response time (to load steps and when synchronizing).

- Controlled variable(s): The size of the load was generally held constant, given the ratings of the storage, PV and generators for the various cases described in Section 3. Ability to control the Chiller #3 load level was limited. When varying load level was required for particular demonstrations, variable resistive load banks were employed.

- Hypothesis: The hypothesis is that power optimized storage can support the microgrid to maintain power quality given generator response limitations, and PV power limitations. Also, PV with microgrid controls in conjunction with storage can maintain microgrid power with minimal use of generators. The performance objectives detailed in Section 3 provide further details.

- Test Design: The tests were designed to obtain the data for each performance objective described in Section 3. The microgrid voltage and frequency were monitored and recorded for power quality, as were the output levels (kW and KVAR) of the storage, PV, and generator sources. Loads were stepped on/off (as described) or held constant as needed. The battery SOC was monitored. Battery support of generator tests was also done with a reduced battery capacity to aid in quantifying how much battery power is needed for a given generator rating to obtain the desired performance objectives. Similar reduced battery capacity testing will be done for PV related tests. The IAPS system provided a connection and measurement point for the variable resistive load as needed.

- Test Phases: The testing phases consisted of commissioning the updated storage system and the new PV system, and then performing the demonstrations. The demonstration phases will be of three types.

    1. The first type of demonstrations were done to evaluate performance objectives related to storage system and generator interaction, related to ramp rate, load step and generator synchronization type performance. These were done over the course of days, when possible, and were repeated as needed to cover data collections, and to assess any observed anomalies.
    2. The second type of demonstrations were done to evaluate PV system performance objectives with storage support, related to managing variable loads, variable solar, ramp rate control of PV, PV inverter VAR support, and MG support with PV and storage alone. These were done over the course of days when possible and were repeated as needed to cover data collections, and to assess any observed anomalies.
    3. The third type of demonstration was done to evaluate PV and storage with generator interaction. These long duration tests were to evaluate performance objectives related to quantifying fuel savings (i.e. islanded operation with and without PV available), and to quantify storage needs (number of operations and power output).

5.2 BASELINE CHARACTERIZATION

- Reference Conditions: The baseline conditions that were measured are generator synchronization time, generator response time to load steps, generator fuel use (estimated given load and efficiency curves), chiller load inrush kVAR demand at startup, microgrid (islanded) steady state power quality, utility steady state power quality, and storage battery charge/discharge time and energy (SOC: 30%-to-90%,

90%-to-30%) at full power. The generators were warmed up by running them for 20 minutes. For PV related tests the load was selected based on the typical PV power availability.

- Baseline Collection Period: The baseline data collection period was over several days, prior to performing demonstration tests during a given test period. Baseline PV data was collected over full days.

- Existing Baseline Data: There is no existing baseline data.

- Baseline Estimation: There is no existing baseline data.

- Microgrid Load Availability: The designated load for the microgrid is Chiller #3 in the 5900 Francis Street Building. For much of the data collection period, Chiller #3 was non-operational due to the failure of a pump associated with the chiller. This pump was not repaired (by Fort Sill personnel) until late May 2014. As a result, it was necessary to load the microgrid with resistive loads which were connected at each of the IAPS inverters. All tests prior to June 2014 made use of these resistive loads.

- Data Collection Equipment: For collecting the data prior to the availability of Chiller #3, a Fluke 1750 was connected to the IAPS breaker to monitor the voltage, current, frequency, and phase of the microgrid output to the resistive loads. The recording interval was continuous during the entire collection time with the sampling rate automatically increasing during transient events. In June of 2014, when Chiller #3 became available, a "Red Lion" data collection device was added to the measurement suite within the CAT-ISO switchgear which is already measuring the energy parameters of each of the microgrid generating components and load as well as the utility. The Red Lion provides a time stamped record of the data. The parameters collected are the RMS voltage, current, frequency, kW and kVAR of the microgrid in an islanded condition. Data samples are taken every two seconds. Also in June, the location of the Fluke 1750 was moved from the IAPS breaker to the main power bus also within the Caterpillar switchgear to monitor system loads. The sampling rate of the 1750 is better for recording transient events. For longer duration tests the same collection equipment was used. The Solar radiation will be tracked during the day to correlate the ELCC of the array for the days the data was collected to the load that was connected to the system. (Never measured insolation, information may be available on line.) An Eaton PXM2000 energy meter is embedded in the solar inverter connected to the new PV array. The PXM2000 maintains a 90 day record of the inverter output.

5.3 DESIGN AND LAYOUT OF SYSTEM COMPONENTS

- System Design: The overall system is a low voltage microgrid with several internal sources, storage, renewables, and a few large loads. The demonstration shows that power optimized storage (as opposed to high energy) can support microgrid power quality with generators and renewables. The demonstration shows that high penetration renewables

can be used within a microgrid to provide stable power when supported by storage and coordinated with generators. The power optimized battery system is commercially available (from Altairnano). The PV array is standard commercial equipment, while the PV inverter is a standard Eaton unit with a control interface allowing for microgrid enabled performance.

- System Depiction: The full Fort Sill microgrid system is shown in Figure 20. The items being added for this demonstration project are the expanded PV system and the power optimized battery system. An existing storage inverter was reused for the power optimized battery system

- Components of the System: The main elements of the microgrid system are the following:
  - Microgrid interface static switch: This is a fast (sub-cycle) switch for rapidly disconnecting the microgrid from the utility, and is shown in Figure 21.

Figure 21: Microgrid Intertie Static Switch (MISS) Layer Zero

  - Natural gas generators: These are two CAT natural gas generators (240kW) (as shown in Figure 22) intended for emergency backup power. They are used as power sources when islanded as needed for the demonstration.

Figure 22: Caterpillar 240kW Nature Gas Generators

- Windmill: A small 2.5kW rated windmill is a renewable source within the microgrid, as shown in Figure 23.

Figure 23: 2.5kW Wind Generator

- Existing PV: A standard 17kW PV system is a renewable source that existed within the microgrid prior to this project, as shown in Figure 24.

Figure 24: 17kW PV array (upper) & PV Inverters 6kW/phase (lower)

- 86kW PV system: This microgrid enabled PV system (as shown in Figure 25 and Figure 26) was added for the demonstration of high penetration PV withinmicrogrids. The PV inverter has a 250kW rating, which provides capacity forkVAR support. If the PV inverter is islanded with no other source present (no generators or storage inverter) it will shut down for at least five (5) minutes (per IEEE Std 1547, anti-islanding). It will then try to reconnect if the utility or a local microgrid source (generators or storage inverter) is present.

Figure 25: 86kW PV Array

Figure 26: 86kW Array PV Inverter

- Storage system: The power optimized storage system is composed of a 400kW (two parallel 200kW units) battery system having a 56 kW/Hr total capacity, as shown in Figure 27. The storage inverter is a 500kVA rating unit (shown in Figure 28)–intended for a prior microgrid demonstration (with a flow battery

system). The storage inverter keeps the frequency and voltage within limits to prevent the PV inverter from sensing that the system is operating in an islanded manner.

Figure 27: 400kW Power Optimized Storage Battery


Figure 28: 500kW Storage Inverter

- IAPS: “Integrated Auxiliary Power System” is a system intended to demonstrate interconnection of microgrids and utilities with different frequencies (non-synchronized). For this demonstration project, IAPS will serve as a resistive load tie point.

Figure 29: Integrated Auxiliary Power System

- Chiller and auxiliary loads: The primary microgrid load is a chiller driven by a 400HP induction motor (shown in Figure 30). The measured full load input is 214kW, 182kVARs, 339amps. The chiller load can be controlled by the automation system. Other loads are present to support the chiller and its processes, and include chilled water loop pump (shown in Figure 31), chilled water process pump, and air compressors.

Figure 30: 350 Ton Chiller - #3

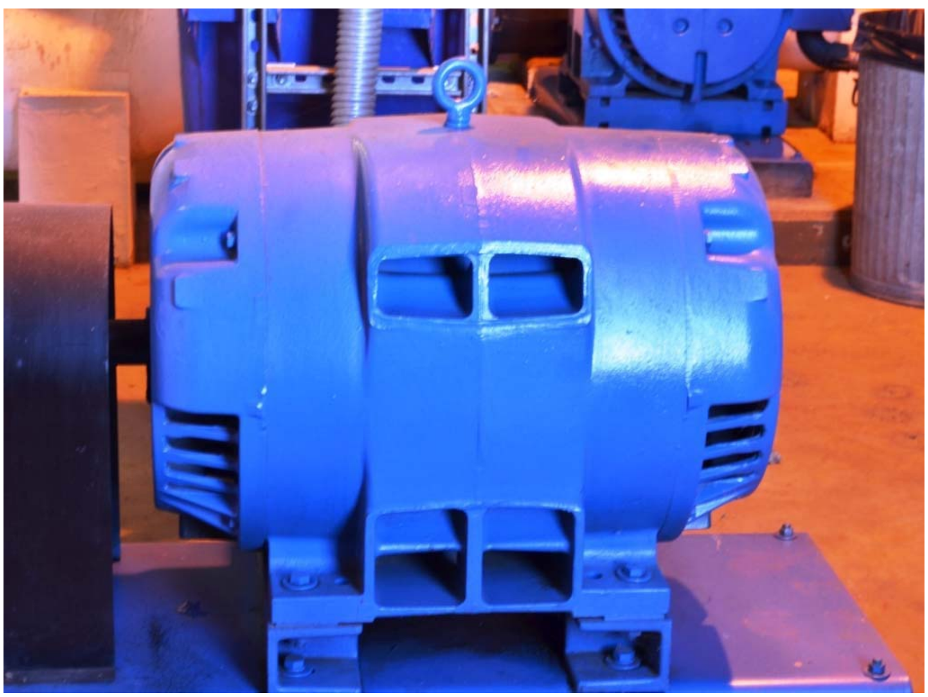

Figure 31: Chilled Water Loop Pump

- Microgrid monitoring units: Three monitoring units are present in the system – 1) storage inverter output (shown in Figure 32) IAPS microgrid output, these units monitor voltage and current.

Figure 32: Storage Inverter Monitoring Unit

- System Integration: The existing Fort Sill microgrid was demonstrated and proven prior to the start of this project's demonstration testing. The PV added connects directly to the existing PV/Wind switchboard input, and its integration is mainly an expansion of capacity. The battery system uses the existing storage inverter and the same switchboard interface, so its integration is mainly an update of controls based on the new battery performance ratings.

- System Controls: The existing microgrid control system is based on ISO EMCP 3.S controllers. Four controllers are networked and manage the system. The controllers are assigned to 1) Utility Interface (MISS), 2) Generator #1, 3) Generator #2, and 4) Storage Inverter. In addition, controller #1 also monitors the IAPS unit resistive load, while controller 4 monitors the PV/Wind output. In addition to managing microgrid modes, this system enables sharing of source/load data between all the microgrid sources. This enables optimization of controllable PV output, and storage system response within limits on communication and parameter/data updates.

5.4 OPERATIONAL TESTING

- Operational Testing of Performance: The battery storage and PV inverter system is added onto the existing microgrid at Fort Sill. The generators are natural gas generators. These generators are installed onsite to meet the microgrid operational requirements. For synchronization time demonstration and performance evaluation, the microgrid will be operated in a manual mode such that the generators can be started one after the other to determine the time to start. The battery inverter system is capable of operating in parallel with the generators to support the generators in both real and reactive power. The data collection approach was as described above in "Baseline Characterization 1.2 Data

Collection Equipment”. The generators and the storage inverter have protection relays that will be set for over-under voltage and over-under frequency protection when the generators are starting and will prevent the load(s) from going out of control. The PV array and the inverter are added to the microgrid at Fort Sill. The load on the PV with energy storage system can be adjusted using the variable resistive load banks. The load on the PV with energy storage system will be set up with clear limits of over-under load conditions and the systems will be ensured to operate safely. It was determined that the long duration demonstrations would be problematic given the realities of the loads available at Ft. Sill. Long term tests were generally shortened from 30 days to 5 or less. The reason for the change is that the primary destination for chiller (the load) water was the Starship buildings. In the event of a base-wide utility outage, the microgrid could operate, but the Starship buildings could not. So any pumped chilled water could not be used since destination air handling equipment was unpowered. Therefore, unsupervised islanding was not allowed by base personnel. All tests needed to be performed with Eaton staff on site. The renewable generating sources were allowed to run continuously, however.

- Modeling and Simulation: A complete system model is available in PSCAD. The Fort Sill microgrid elements have been modeled in PSCAD and the different operational sequences have been simulated for the prior microgrid demonstration project. These simulated natural gas engine models will be verified for transient performance and the battery inverter model will be used to simulate the two under different starting load conditions. The simulations will be used for measurements and system setup. As part of the IAPS project, extensive modeling of the PV, energy storage, and average models for inverters were developed in PSCAD. These models can take any profile from any city and the models predict the available PV power. This model will be used with different load profiles to evaluate the performance of the integrated system. These models were used to evaluate the power quality during such an operation. These models were verified as well as used to determine the proper sizing of the loads as well as setting the protection features in the inverters for safe operation.

- Timeline: The demonstration began on March 11, 2014. The demonstration testing was completed on October 17th, 2014. Five testing sessions at Fort Sill were each five business days in length and occurred on the following dates:
    - March 10 through 14, 2014
    - April 14 through 18, 2014
    - June 2 through 6, 2014
    - August 4 through 8, 2014
    - October 13 through 17, 2014

- Technology Transfer or Decommissioning: The demonstrated equipment added for ESTCP will not be removed from the site. Ft. Sill DPW personnel, contract electricians and Energy Operations staff were trained on microgrid operations, focusing on exercising the NG generators under load and performing maintenance charge and balancing of the battery packs. This training was presented on October 16, 2014. All microgrid

automation was left disabled with the Static Switch by-passed. Chiller #3 will be retired for the fall and winter months and microgrid back up will not be needed. The training presented included instruction for users to start each component of the microgrid. The IAPS units will be disabled, as a programmable load will not be needed during normal use.

5.5 SAMPLING PROTOCOL

- Equipment Calibration: All monitoring equipment will come with a current one year calibration from the manufacturer or a certified calibration laboratory.

- Quality Assurance Sampling: The sampling frequency will be set at the device level to suit each test. Fast response events will be sampled in milliseconds to seconds, while longer duration events will be sampled at intervals of several seconds to one minute.

- Data Description: Data collected includes kW, kVARs, Volts, Hertz, Ampers Seconds. The number of samples vary based upon the particular demonstration test, but are sufficient to provide full resolution of the duration of event being monitored. The BMS (Battery Management System) has an integral data logging capability. This was used to acquire data for selected short duration tests, and most long duration tests. Parameters include SOC and voltage of individual cells.

- Data Collector(s): Data was collected by Eaton personnel on site at the time the tests were run. PV data was collected over a longer term by integral monitoring units described earlier.

- Data Recording: Data will be collected both manually and through automated systems. Manual data collection will be done for short duration demonstration tests (e.g. ramp rates, load steps, etc.).

- Data Storage and Backup: All manually collected data will be backed up to laptop hard drives on the day acquired. All automated collected data will be copied from SD memory cards to laptop hard drives when SD cards are swapped out.

- Data Collection Diagram: Not applicable.

- Non-standard Data: Not applicable.

- Survey Questionnaires: Not applicable.

5.6 SAMPLING RESULTS

- Post-Processing Statistical Analysis: No significant post-processing statistical analysis is planned.

6 PERFORMANCE ASSESSMENT

The following subsections provide a performance assessment of the demonstration objectives given in Section 3. Each of the thirteen (13) objectives is a subsection. A common format is used in the discussion whenever applicable. This format is:

- *Objective: The high level description*
- *Test Sequence: The sequence of events that makes the test results understandable*
- *Test Data: Highlight plots of data with an explanation. Table(s) that summarize multiple test runs (if applicable)*
- *Conclusion: The significance of the demonstration result(s)*

Notes regarding the demonstration discussions: The following is a summary of the microgrid system sequence of operation for a typical utility failure. This is the basic mode of operation that would cause the microgrid to island. The islanded mode of operation is one that applies to most of the demonstrations. This sequence is given here as a common example applicable throughout the demonstration discussions.

Intended Microgrid Operation Sequence in Response to Utility Outage or Power Quality Fault

In the event of a grid fault, the following steps are designed to be taken by the microgrid for transition to an islanded condition:

1. Grid outage or fault detected
2. Static switch opens (islanded)
3. Energy storage subsystem services the microgrid load
4. Generator 1 Starts
5. Generator 1 synchronizes with the storage inverter (SI) and connects to microgrid bus
6. SI and Generator 1 begin to share load
7. Generator 2 starts
8. Generator 2 synchronizes with the microgrid power bus and connects
9. SI transfers remaining load to generators and goes to zero power export
10. Microgrid controls determine if there is sufficient islanded generation to charge batteries
11. SI charges batteries (imports power) if possible
12. Microgrid maintains load mainly managed by the generators and supported by the renewables

Transition from islanded back to grid connected status occurs automatically when the utility returns or the fault is cleared:

1. Return of normal utility grid condition is detected
2. Generators synchronize with utility grid
3. Static switch closes
4. Generators transfer load to utility
5. Generators disconnect, cool down and stop
   - <u>Industry Standards</u>: IEEE 1547 "IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems" will be used to define the power quality

limits that the microgrid will operate within for several of the performance objective demonstrations. Suitable power quality is defined as voltage maintained within +10% /-12% and frequency within 60.3Hz/59.3Hz the requirements for IEEE 1547.

- Rapid Validation of PV Power: When a test required variation of renewables it was simulated with changing the size of the array by connecting and disconnecting sub-arrays. This was more effective than waiting for rapidly moving cloud shading to provide the desired power variation for the demonstration.

- Due to the site limitations on running the natural gas generators, only on a true power outage the generators were run for short durations and their performance was extrapolated when longer term data was required.

6.1 Demonstration 1: Load support with rapid generator synchronization

Objective: Synchronization of both generators within 30 seconds. No loss of microgrid loads.

CAT-ISO Control Automation Timers
Timer T2 controls the length of time between the detection of a utility fault condition and the starting of Generator 1. The majority of utility disturbances are less the 30 seconds, thus the default setting for T1 is 30 seconds. This period prevents the generator from being started on each brief utility disturbance of less than 30 seconds. The energy storage system allows the microgrid to "ride through" short disturbances. Timer T3 controls the length of time between the generator 1 start and the generator 2 start; it also has a 30 second default setting.

Test Sequence:

1. A load of 25kW resistive, plus ambient reactive loads are active – totaling 108kVA
2. Generator timers T2 and T3 are set for 30 seconds (30 seconds from utility outage to Generator 1 start, then 30 seconds until Generator 2 starts) for baseline system synchronization tests. T3 will be adjusted downward to demonstrate rapid synchronization.
3. Energy storage (SOC ~80% at each Test start) and renewable subsystems are enabled
4. The microgrid is islanded "unintentionally" (a grid power quality fault is simulated)
5. The islanding process (rapid synchronization) test was repeated four times with the time settings as described in item 2
6. Time stamped data samples (Red Lion) were recorded times of events in the test process – Islanding to both generators synchronized and carrying the bulk of the microgrid load
7. Power quality information is recorded be the Fluke 1750 Power Recorder

Test Data – "Default" Synchronization Baseline Tests
The Plot (Figure 33) and the data in Table 2 below illustrate the microgrid's process of islanding, start and synchronization of each generator over roughly a 78 second period using the T2 and T3 30 second default settings. The total synchronization process exceeds the 60 seconds of the timers due to other system latencies, probably mechanical.

Power Quality During “Default” Synchronization**:**
Figure 33 above also illustrates that although there are variations of voltage and frequency they are minor (they appear dramatic due to the granularity of the vertical axes). It is clear that there is no loss of microgrid load as stated by the performance objective. Plus voltage and frequency are maintained within IEEE 1547 voltage and frequency limits throughout the islanding process.

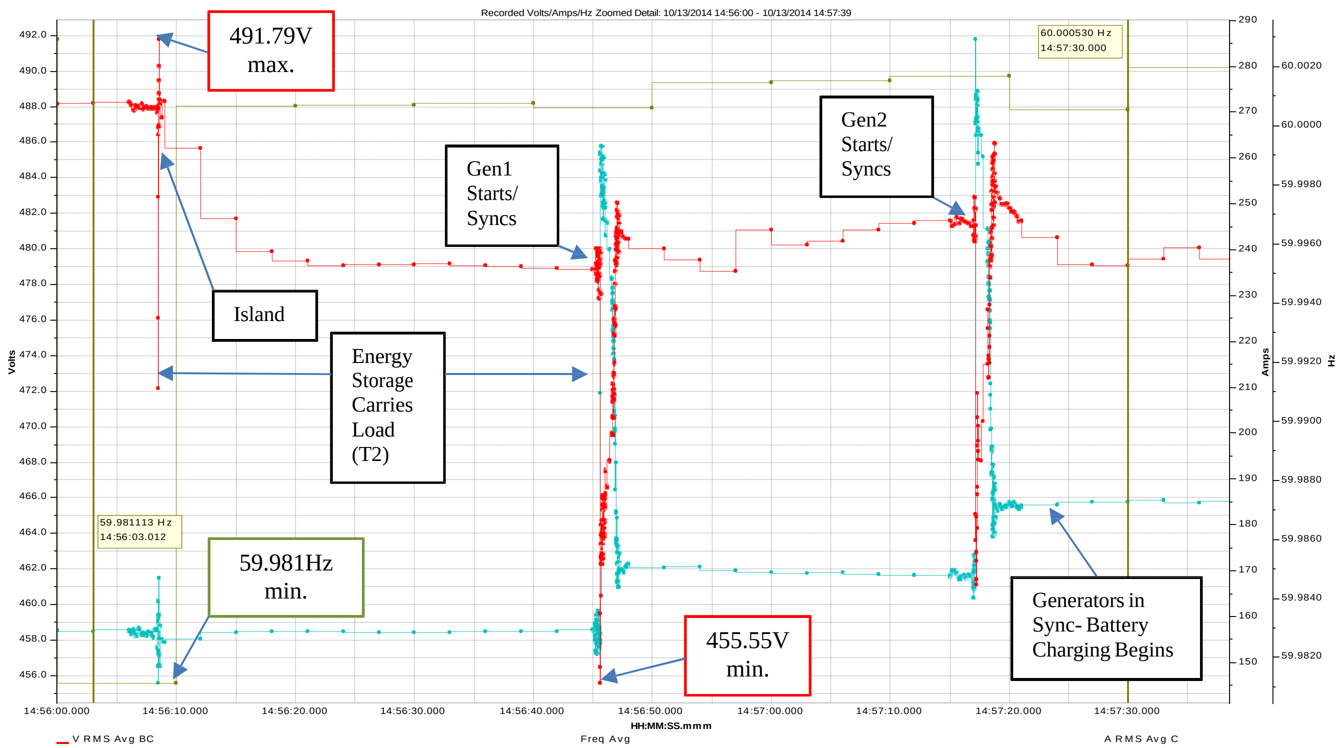

Figure 33: Synchronization Using Default Timer Settings

Figure 33 above is typical for the tests documented in Table 2 below:

Table 2: Tests 1-4

Test Event TOD/Δt	Test 1	Test 2	Test 3	Test 4
Unintentional Island	14:21:42	14:34:02	14:45:12	14:54:08
Generator 1 Start	14:22:22	14:34:40	14:45:52	14:54:48
Generator 1 Sync	14:22:28	14:34:46	14:46:00	14:54:54
Generator 2 Start	14:22:52	14:35:12	14:46:24	14:55:20
Generator 2 Sync	14:23:00	14:35:18	14:46:30	14:55:26
Δt Island to Gen1 Sync	46 seconds	44 seconds	48 seconds	40 seconds
Δt Gen1 Sync to Gen2 Sync	32 seconds	32 seconds	30 seconds	32 seconds
Δt Island to Both Gen Sync	78 seconds	76 seconds	78 seconds	72 seconds

Power Quality:
Figure 33 above also illustrates that although there are variations of voltage and frequency they are minor (they appear dramatic due to the granularity of the vertical axes). It is clear that there is no loss of microgrid load as stated by the performance objective. Plus voltage and frequency are maintained within IEEE 1547 voltage and frequency limits throughout the islanding process.

Test Data - Rapid Synchronization Tests:
To reduce the overall islanding period (island to both generators in sink) T3 was changed from 30 seconds to 3 seconds. T2 will remain unchanged as do the other items described in the test sequence. Figure 34 below shows the islanding process using the new T2 setting.

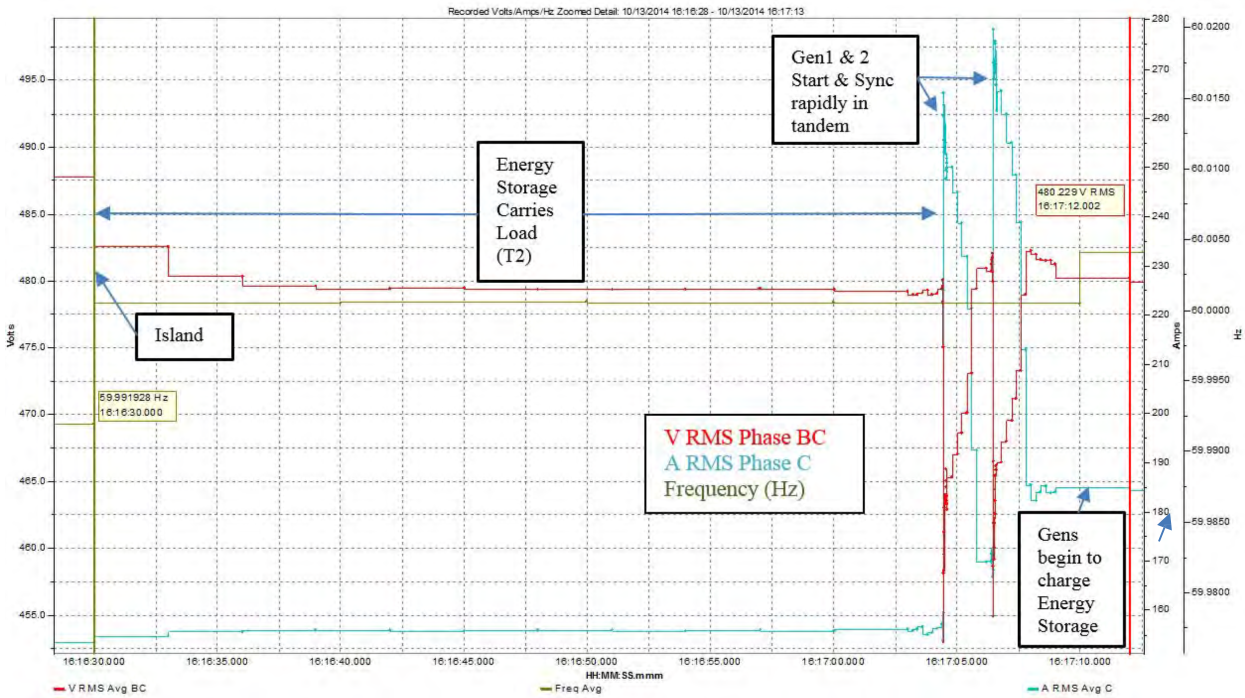

Figure 34: Rapid Synchronization Test 8

Figure 34 above is typical for the tests documented in Table 3 below:

Table 3: Test 5-8

Test Event TOD/Δt	Test 5	Test 6	Test 7	Test 8
Unintentional Island	15:32:44	15:40:46	15:50:26	16:05:30
Generator 1 Start	15:33:24	15:41:36	15:51:06	16:06:10
Generator 1 Sync	15:33:30	15:41:42	15:51:12	16:06:18
Generator 2 Start	15:33:26	15:41:40	15:51:08	16:06:12
Generator 2 Sync	15:33:32	15:41:48	15:51:16	16:06:20
Δt Island to Gen1 Sync	46 seconds	50 seconds	48 seconds	48 seconds
Δt Gen1 to Gen2 Sync	8 seconds	8 seconds	4 seconds	2 seconds
Δt Island to Both Gen Sync	54 seconds	58 seconds	52 seconds	50 seconds

Rapid Synchronization:
Tests 5 through 8 clearly show that the modified microgrid controls allow the generators to rapidly synchronize and the reduced T2 setting removes about 20 seconds from the islanding process.

Power Quality:
The plots above indicate that the microgrid loads continue to be serviced during the islanding process without power loss or degradation of power quality. Energy storage maintains PQ during transitions from grid connected to microgrid.

Controls Development:
Over the course of testing for Demonstration 1, important control details were determined. The microgrid controls were such that after supporting the load during islanding transition, the Storage Inverter (SI) would hand off "Master" status to Generator 1. The generators as master of the microgrid manage the voltage and frequency. The design of the microgrid controls is such that the generators relinquish the master controls to the SI whenever the chiller is ready to start. During this WYE-DELTA starting of the chiller motor the SI can support the transients better.

Having Generator 1 serve as the master before islanding was complete often prevented rapid synchronization and occasionally caused the transition to microgrid to fail. This is partially due to the size of the generator. Figure 35 shows a plot of system real power during a transition in which master status was passed from the SI to Generator 1. Generally, as the islanding transition is concluding, the SI transfers the microgrid load to the generators after they have synchronized. When the SI load is zero and if the microgrid has excess generating capacity, the SI will use the excess generation to charge the battery. In the instance plotted below, Generator 2 is not able to sync until 3 minutes after Generator 1 has. This is due to Generator 1 having to carry both the microgrid load and charge the battery, because of this loading Generator 1 is not providing a stabile frequency reference for Generator 2. Essentially, Generator 1 ends up being unsupported by Energy Storage and the frequency drops and varies excessively. In this case, the microgrid was loaded by chiller #3.

Power Quality:
Without a solid frequency reference to bring all generators online in a timely manner power quality issues arise. As stated elsewhere in the document, power quality (PQ) is defined as voltage maintained within +10% (528VAC) and -12% (422.4VAC), and frequency within 60.3Hz and 59.3Hz by the IEEE 1547 standard. Figure 36 illustrates out of IEEE 1547 both upper and lower frequency limits during prolonged synchronization. Figure 37 illustrates voltage events that approach the 422VAC lower limit during this microgrid transition.

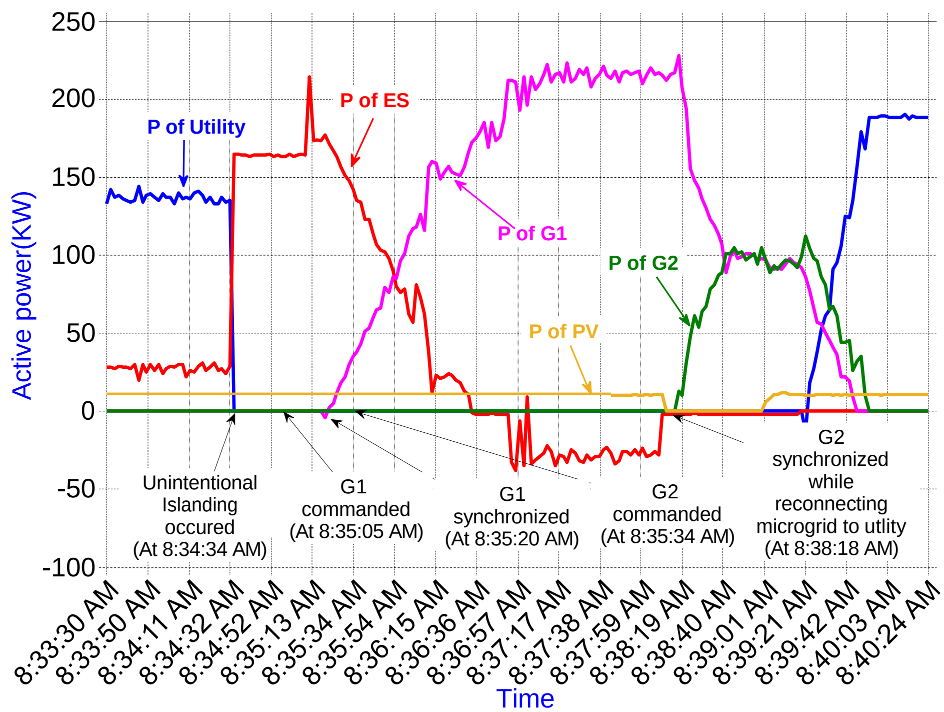

Figure 35: Prolonged Synchronization (Unsuccessful Microgrid Transision)

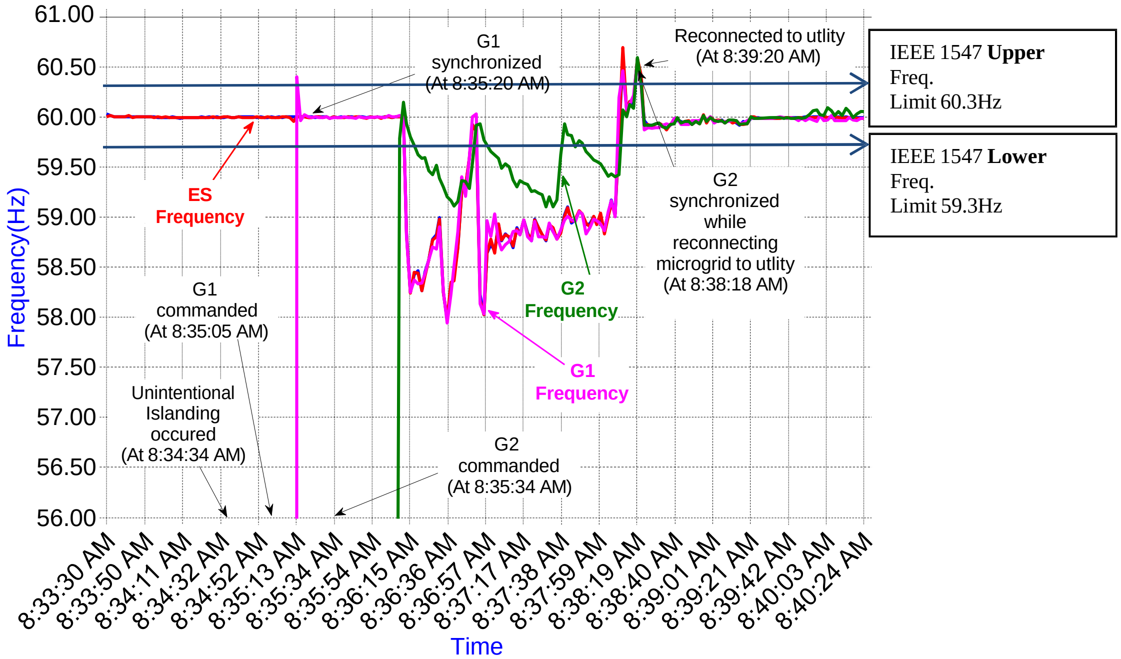

Figure 36: Out of Limit Frequency Deviations During Transition

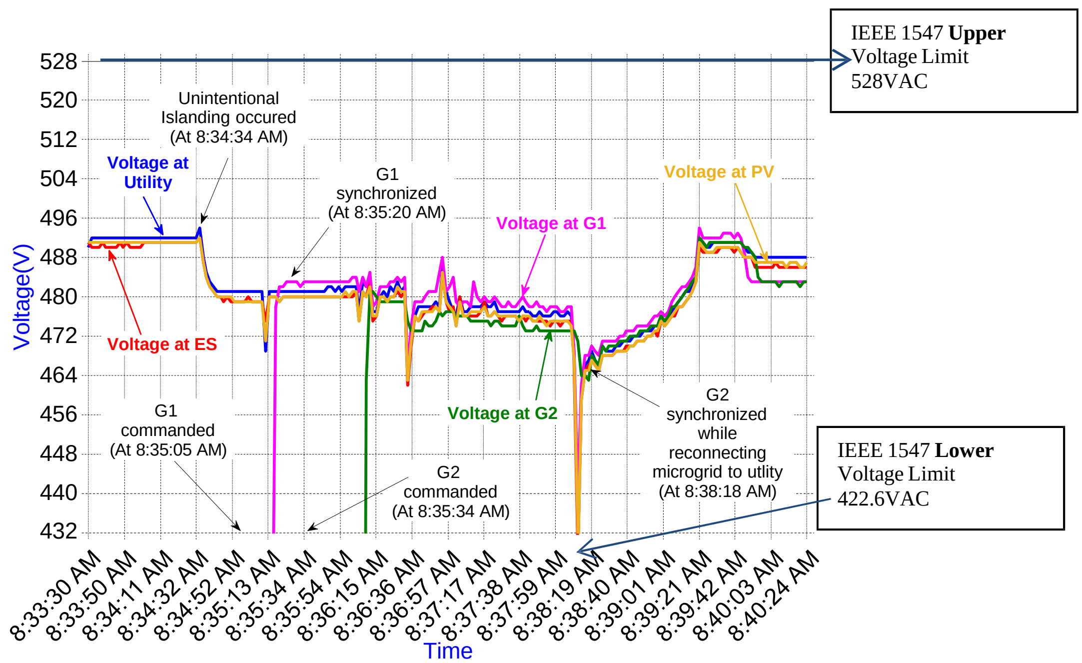

Figure 37: Voltage Deviation During Transition Approaches Lower Limit

The practice of handing off master status from SI to Generator 1 during islanding transition was changed in favor of having the SI retain master status until islanding is fully complete. The SI will also take master status from the generators when the chiller is called to start. The Storage Inverter is configured to counter act the frequency droop characteristics of the natural gas generators – energy storage supports the load. With the SI acting as master generator, a solid

frequency reference is maintained during islanding transitions and islanded chiller starts. Figure 38 illustrates an islanding transition with the SI serving as master throughout.

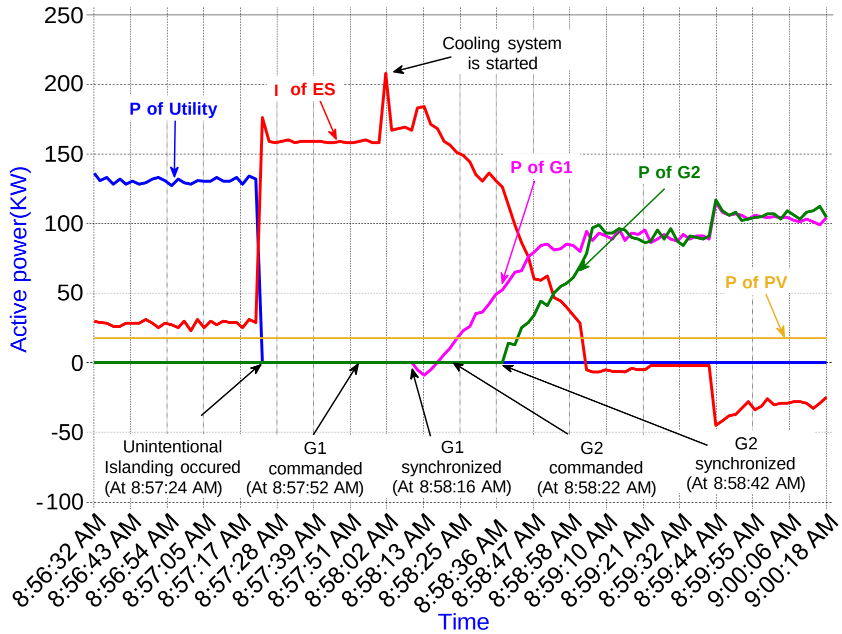

Figure 38: Energy Storage Maintains Frequency Reference and Provides Load Support Throughout Islanding

With energy storage load support, power quality issues are minimized during islanding transition: Figure 39 and Figure 40.

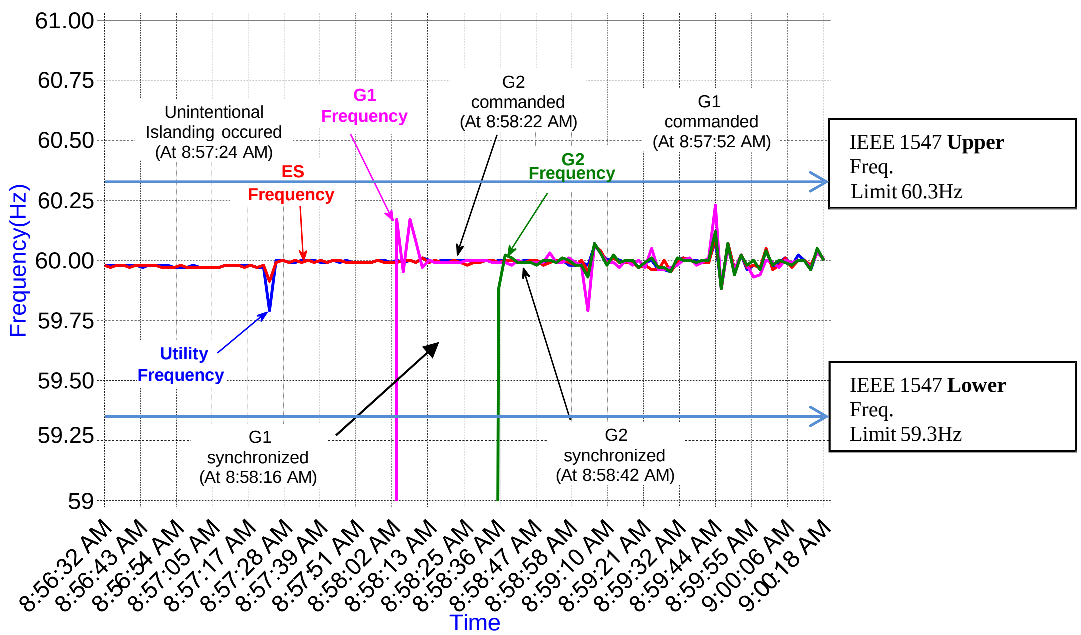

Figure 39: Frequency held within Specified Limits

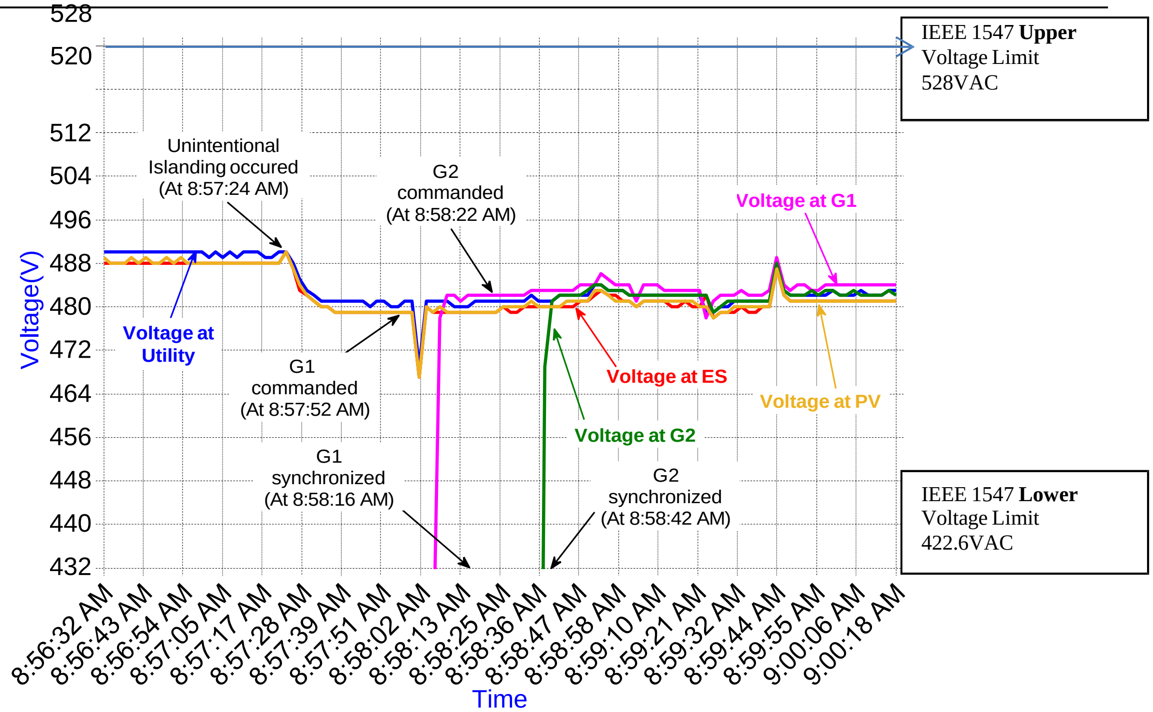

Figure 40: Voltage held within Specified Limits

Demonstration 1 Conclusion:
The microgrid controls with the storage inverter taking the master role and the legacy generator synchronizing to the SI does allow for rapid synchronization of the generators without loss of microgrid loads. During these transients the power quality is maintained within IEEE 1547 limits. The selection of the energy storage technology and size and the design of the storage inverter and its controls result in the desired performance.

6.2 Demonstration 2: Load step support to recover voltage and frequency

Objective: This demonstration shows that power optimized storage is able to support the microgrid voltage and frequency during a load step, thus reducing the time required for the voltage and frequency to stabilize.

Test Sequence – With & Without Power Optimized Energy Storage Support:

1. Microgrid in islanded status
2. Variable resistive load applied at IAPS Inverters to provide step changes to microgrid load
3. Microgrid power quality response to step load changes captured in data acquisition
4. Microgrid power quality stabilization time response, with and without energy storage support, parameters will be compared. Recovery (stabilization) is the time between the application of the step load and stabilization of the microgrid voltage and frequency

Test Data:

Table 4: Load steps applied to generator without energy storage or PV support

Step Load	30kW	30kW	30kW	30kW	50kW	100kW
Voltage Max.	484Vac	495Vac	482Vac	483Vac	482Vac	502Vac
Voltage Min.	469Vac	459Vac	473Vac	470Vac	467Vac	418Vac
Recovery Time	15sec	16sec	12sec	7sec	10sec	19sec

Table 5: Load steps applied to generator with energy storage support

Step Load	30kW	30kW	30kW	30kW	50kW	100kW
Voltage Max.	484Vac	484Vac	485Vac	483Vac	482Vac	485Vac
Voltage Min.	471Vac	469Vac	471Vac	470Vac	464Vac	475Vac
Recovery Time	3sec	3sec	3sec	4sec	6sec	6sec
Recovery Time % Improvement	80%	81%	75%	57%	40%	80%

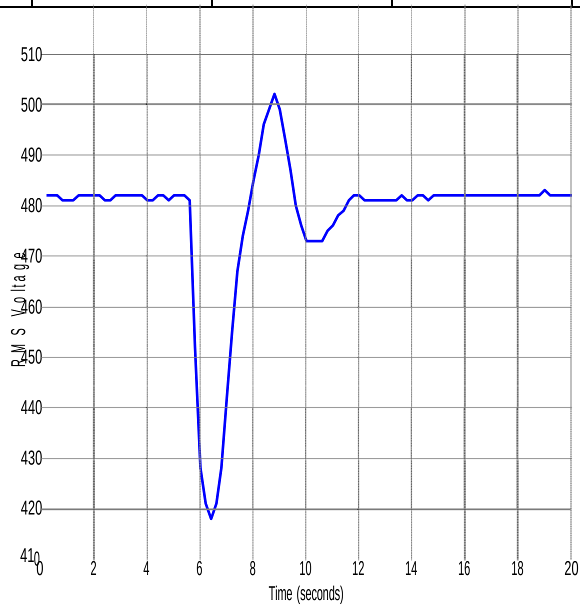

Figure 41: Unsupported 100kW Load Step (Vac)

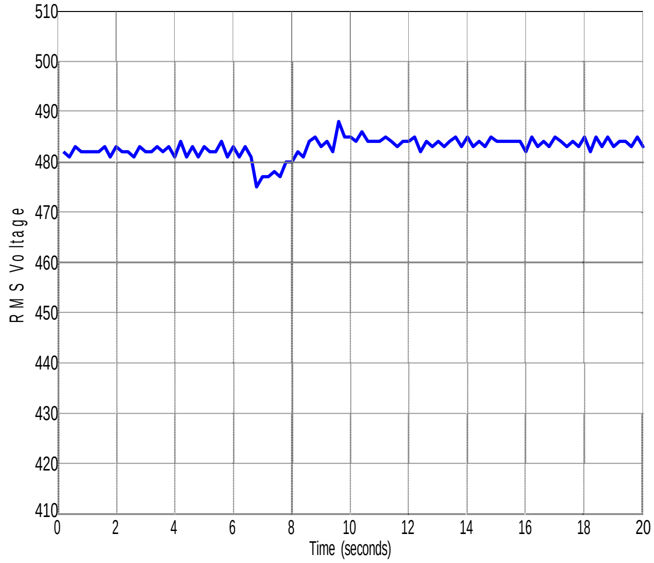

Figure 42: Storage Supported 100kW Load Step (Vac)

Figure 41 and Figure 42 show Microgrid voltage for Unsupported and Supported 100kW load steps. Figure 43 and Figure 44 below show frequency for same tests.

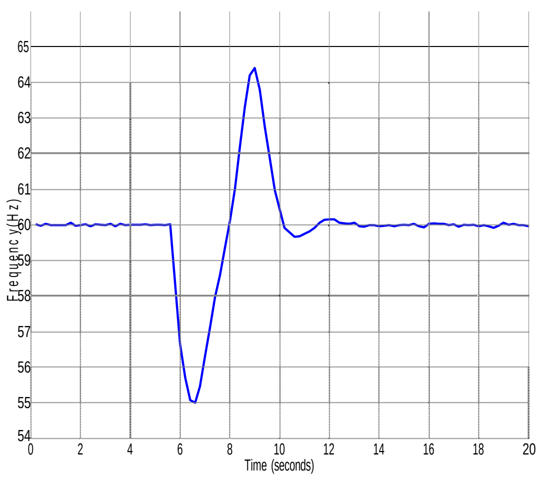

Figure 43: Unsupported 100kW Load Step (Hz)

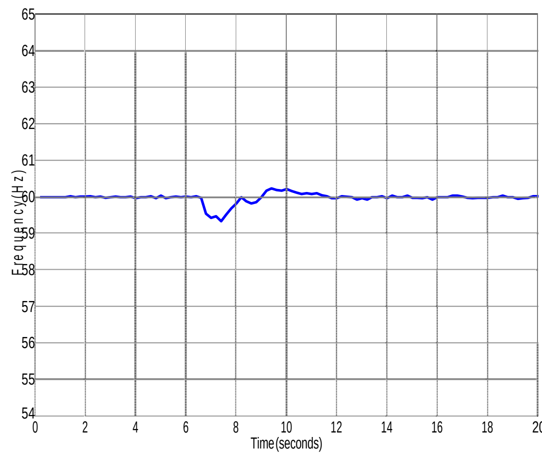

Figure 44: Supported 100kW Load Step (Hz)

The frequency plots above illustrate how the storage inverter, when supporting the islanded microgrid, serves as a highly accurate frequency reference. The unsupported load step response (plot left) shows frequency deviations exceeding both the upper and lower IEEE 1547 limits. The supported plot on the right indicated little frequency deviation.

Table 4 and Table 5 and plots Figure 41 through Figure 44 indicate that with the support of energy storage recovery of voltage and frequency occur rapidly when compared with

unsupported resistive load steps of equal size and meets the 50% recovery time improvement requirement.

Supported and unsupported Chiller Starts:

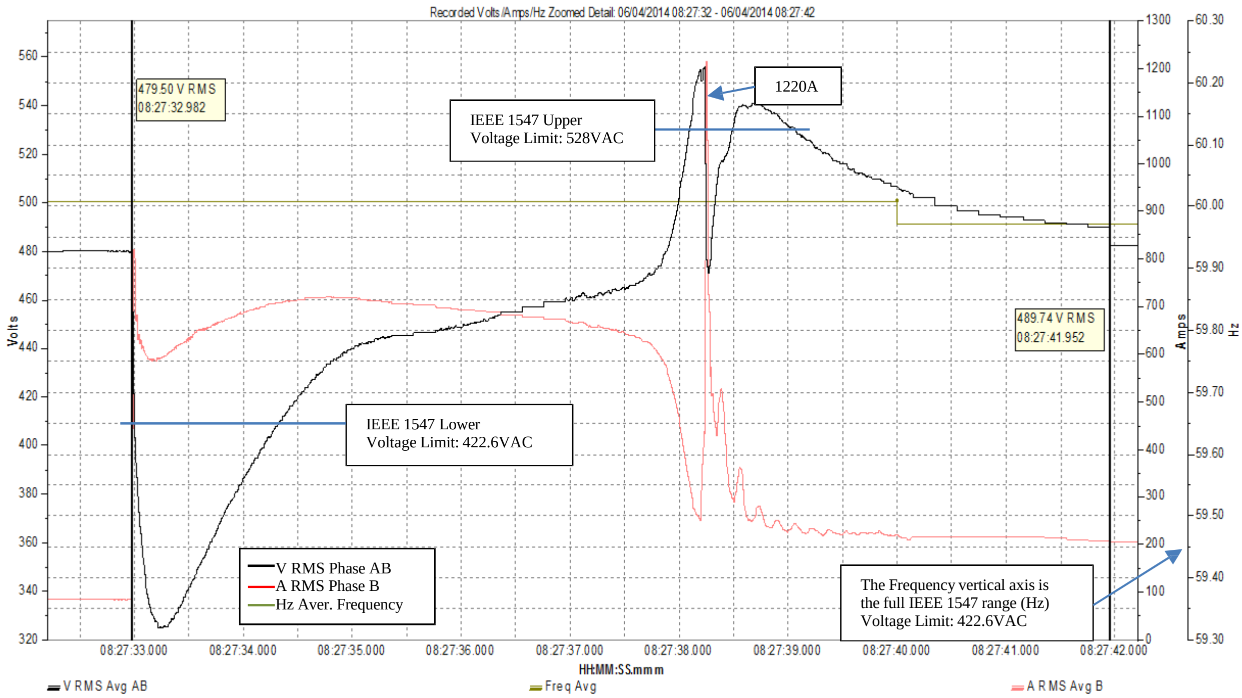

Figure 45: Unsupported (Islanded, Generators Only) Start of Chiller #3

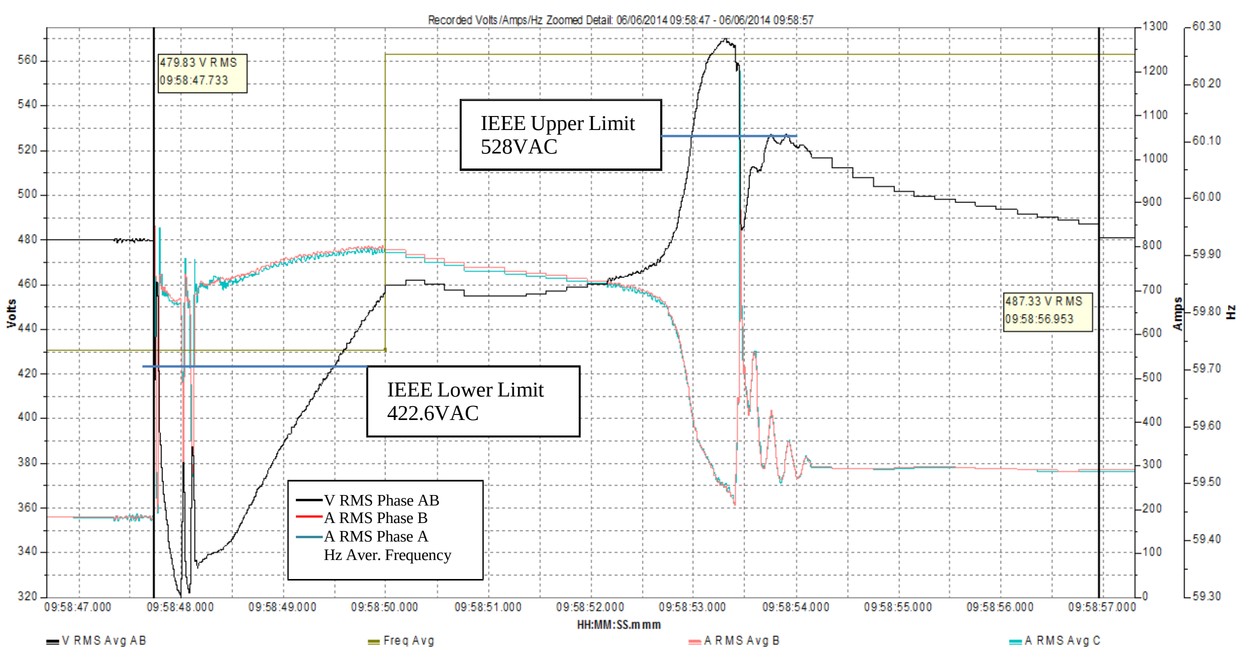

Figure 46: Full Microgrid (Islanded, Supported) Start of Chiller #3

Demonstration 2 Conclusions: This demonstration is designed to test and verify that the storage inverter along with the energy storage can perform well under load changes. The power quality performance of the microgrid during energy storage supported resistive load steps stayed within IEEE 1547 criteria for voltage and frequency. However, performing the more severe, inductive, chiller start (load step) caused 480 bus voltages to exceed IEEE 1547 limits, both low and high, over a 10 second period. The chiller starts of Figure 45 and Figure 46 should be compared with Figure 71 in Demonstration 11 where kVAR support improves PQ during the start. Also, using soft starters in front of the chiller's motor would improve the microgrid's ability to maintain power quality.

6.3 Demonstration 3: Storage powering of microgrid without generators

Objective: Demonstrate the ability of the power optimized storage system to support the microgrid alone (without generators) maintaining power quality for a minimum of 45 seconds to a load representing 60% of the battery capacity.

Test Sequence:
Note: Prior to running this test it was determine that Battery Pack B had a module (20 cells) that was not balancing cell voltages with the other modules, not charging to required SOC and not maintaining charge. This essentially reduced the overall storage energy available for testing. Due to this reduced capacity the 200kW resistive load available should represent at least 60% of capacity.

1. In the microgrid control of the generator 1 start timer (T2) was set to 1 minute, this will prevent the generator from starting before the needed 45 seconds for this test. For some test runs the generators were disabled to allow longer run times
2. Apply 200kW resistive load banks via IAPS breaker
3. Fluke 1750 monitors system load voltage via IAPS bus
4. Unintentionally island the Microgrid – PV2 renewables were allowed to remain connected and operational
5. Starting SOC was set at different levels to help determine any affect that may have
6. Maintain Microgrid load for 45 seconds minimum
7. Minimum SOC of Battery Pack B was monitored and recorded to avoid excessive discharge

Test Data:
Figure 47 below depicts a series of storage only tests over a 22 minute period. The voltage and frequency axes scales are set to represent the IEEE 1547 ranges – Voltage: +10%, 528Vac; -12%, 422Vac – Frequency: 60.3/59.3Hz

Figure 47: A series of 3 “storage powering microgrid” tests

The following Table 6 tabulates the plot above:

Table 6: Test 1-4

Test #	Test 1 (not plotted)	Test 2	Test 3	Test 4
Starting Battery % SOC	63%	62%	58%	60%
Ending Battery % SOC (Pk. 2)	39%	42%	46%	50%
Frequency	Within Limits	Within Limits	Within Limits	Within Limits
Voltage Max.	512Vac	510Vac	515Vac	516Vac
Voltage Min.	474Vac	470Vac	464Vac	465Vac
PV "2" Contribution (kW)	13kW	18.9kW	21.7kW	25.7kW
Load Carry Time	4m 30s	3m	8m 30s	2m

Batteries were charged to the desired SOC between tests. Figure 48 below is an individual plot of Test 3.

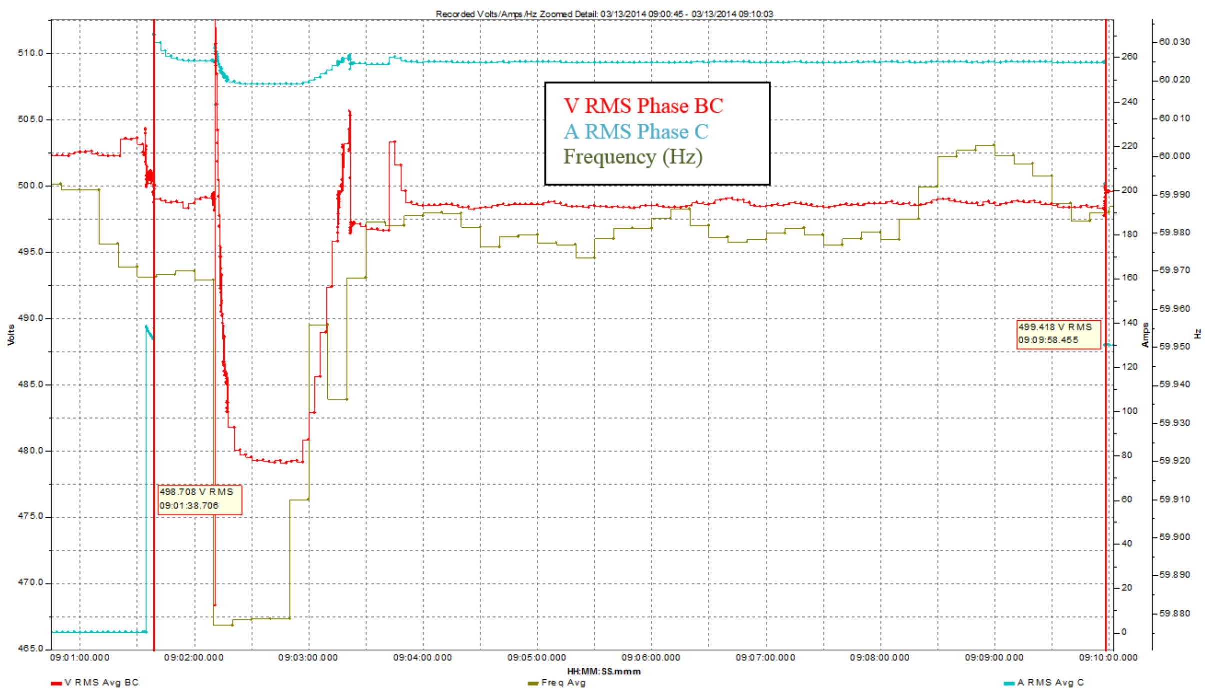

Figure 48: Test 3: SI & PV Drive 200kW Resistive Load for 8 Minutes

Storage and PV (renewables) Powering Microgrid – Chiller Load - Figure 49 (kW) and Figure 50 (Voltage & Frequency)

Chiller loading of Storage & PV tests were run after repairs to Battery Pack B were complete – the battery was at full capacity. The test result plots are shown below.

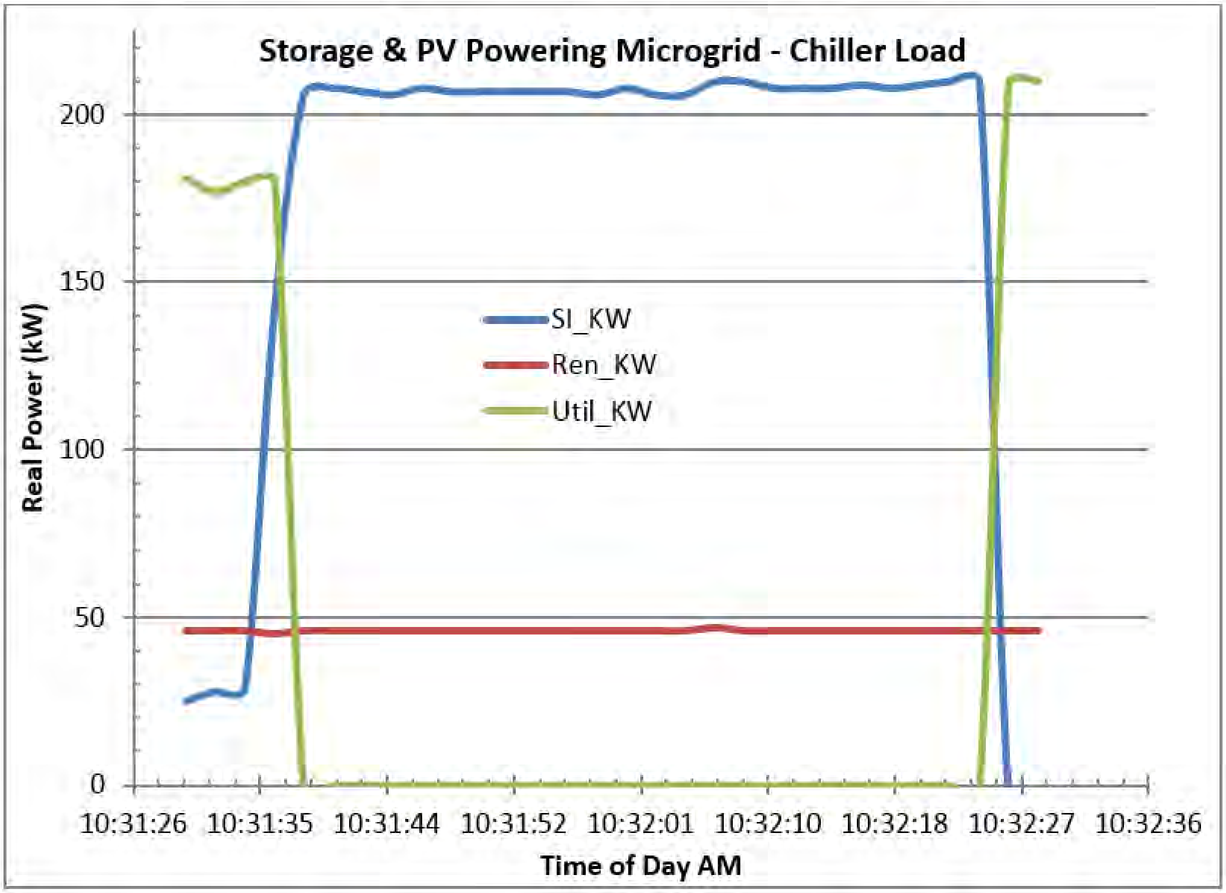

Figure 49: Storage & PV Powering Microgrid – Chiller Load

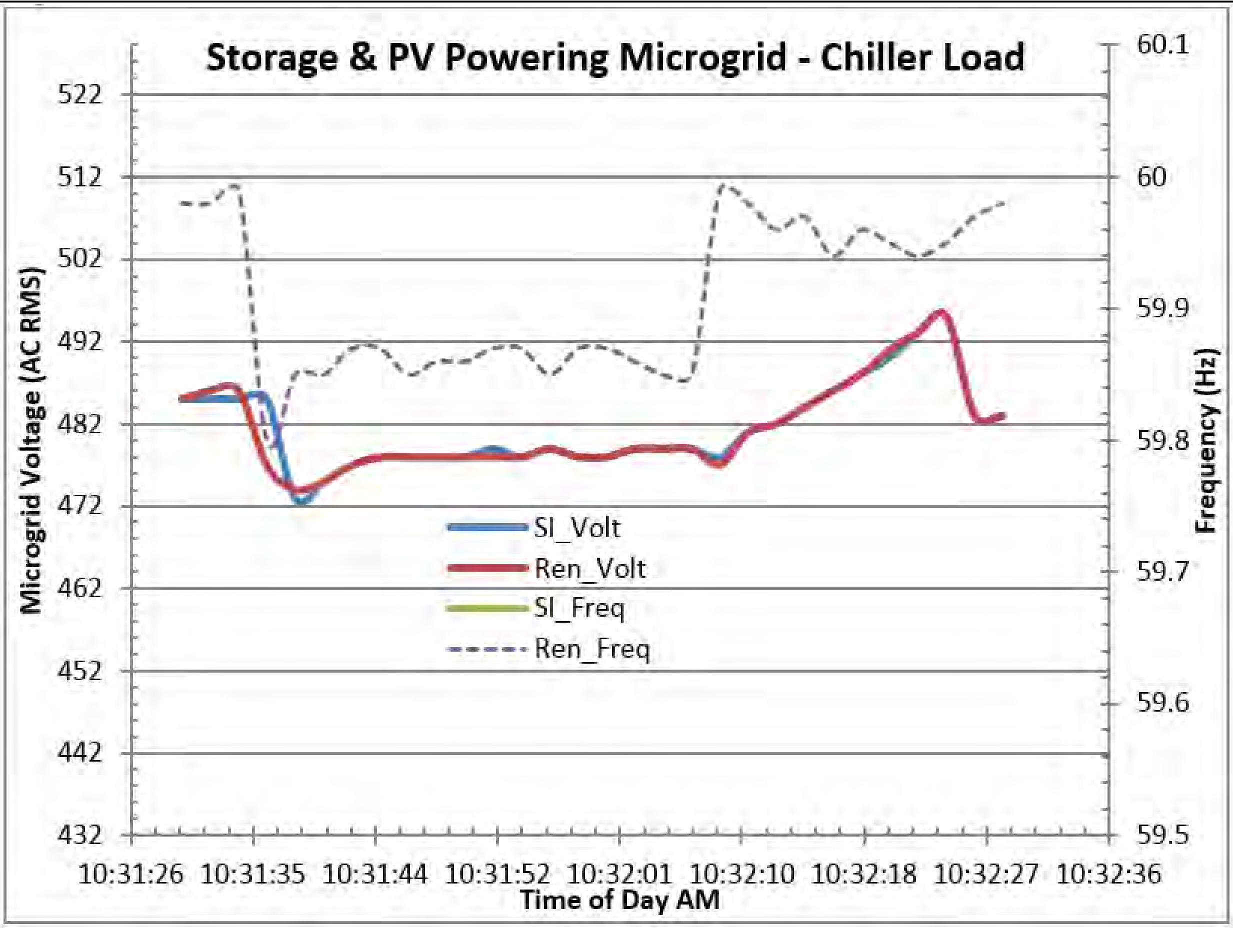

Figure 50: Storage & PV Powering Microgrid – Chiller Load

Demonstration 3 Conclusion:
The demonstration was designed to show that the inverter controls and the battery interface and size can support the entire microgrid. The relatively small (56kWh) energy storage is shown to support the microgrid for 45 seconds. Within 45 seconds, the generators will come online and start sharing power. This delay is also selected such that the generators are not started for short interruptions. As seen the SI returns the microgrid to the utility if the power outage is short. The power quality needs are also met by the SI. In some cases the test data also show the PV inverter stays connected during the transition and supports the SI for the 45 seconds. In each of these cases with about 200kW load the energy storage loses only 10% SOC. This proves the robustness of the design. The battery can be charging after an outage and still be immediately available for a second islanding function. The generator starting delay T2=30 seconds was selected as most interruptions in the US are <30seconds.

6.4 Demonstration 4: Quantify fuel savings given PV for islanded operation

Purpose: This demonstration will quantify the fuel savings provided by high penetration PV in a microgrid where generators are primary sources when islanded.

Test Sequence/Analytical Method: Fuel consumption of the natural gas generators was calculated based on actual running data and published data from the manufacturer. PV output was projected based on actual recorded solar day data, based on a day with full sun, a cloudy day and the day with the most power fluctuations all within a 30 day period.

Test Data/Projected Data: Test performed June 5, 2014:

- While running chiller #3 the microgrid was islanded
- Chiller was operated for 1 hour using only the generators as the source.
- Figure 51 shows the power output of generators running for 1 hour.

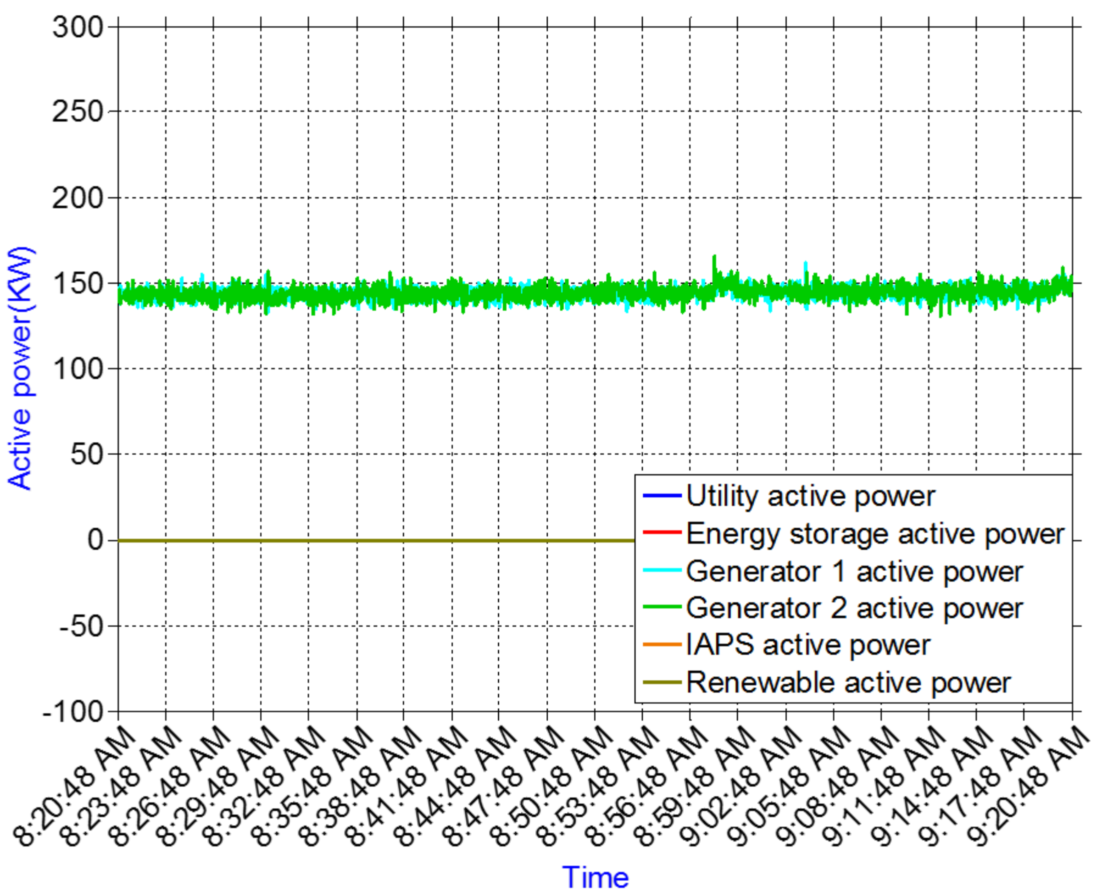

Figure 51: Active Power of generator 1 and generator 2 running in island mode for 1 hour

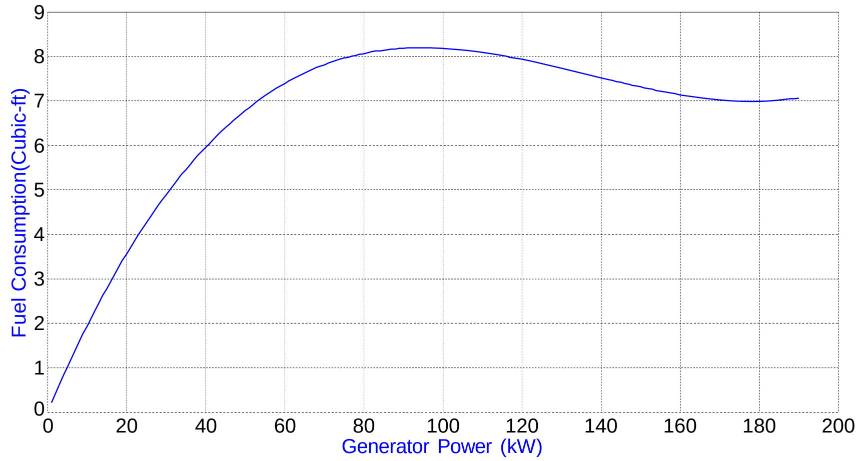

Figure 52: Extrapolated Fuel Consumption curve

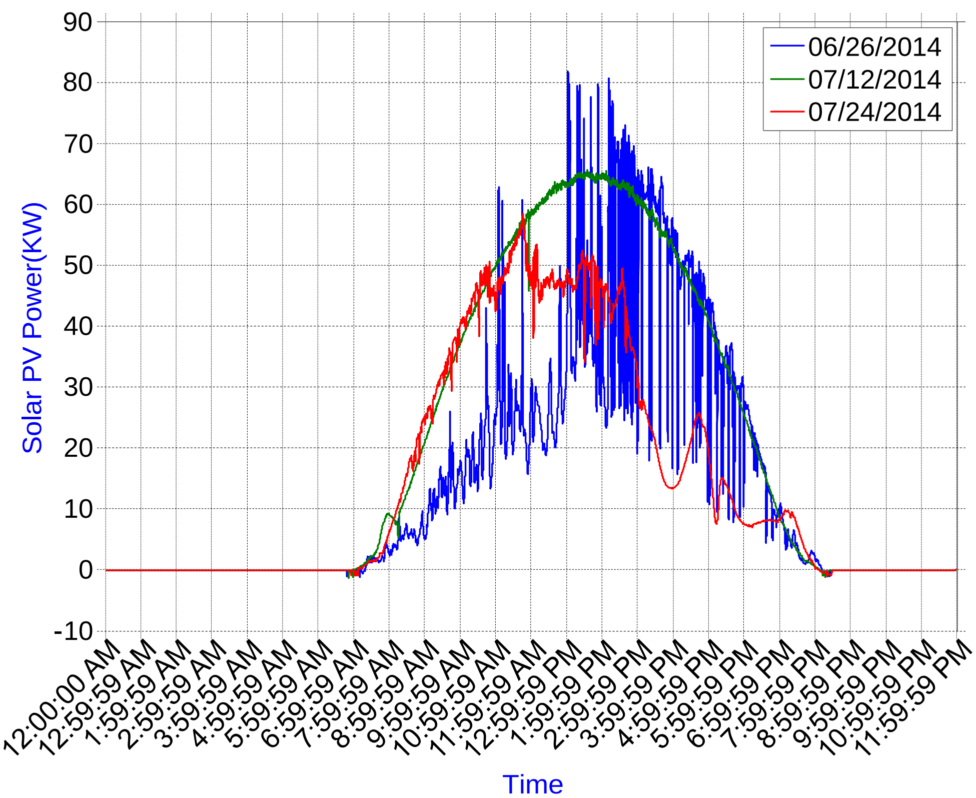

Figure 53: Solar PV day profile for clear full sun day, cloudy day and worst power fluctuation during one month period (Data recorded is the AC power output of the Ft. Sill 84kW array on the 3 days identified, data points are taken every 3 minutes)

Fuel Consumption for engine G3406 (used in the CAT generators) is given in the data sheet for 100%, 75% and 50% load. The data is extrapolated and fuel consumption v/s load curve is derived to calculate the fuel consumption, which is shown in Figure 52. The total energy generated by generator 1 and 2 are calculated for one month period without solar PV. The CO_2 emissions of both generators are also derived for one month period without solar PV. The power profiles for solar PV are measured for one month. The total fuel savings for natural gas generators for one month is calculated after adding solar PV. In addition, the total CO_2 emission reduction is also derived for one month after adding solar PV. Figure 53 shows solar PV power profile for a clear full sun day, cloudy day and worst power fluctuation during one month period.

Table 7: Natural gas generators energy used without solar PV

kW/hr output generator 1 in 1 hour	144.28 kW/hr
kW/hr output generator 2 in 1 hour	144.39 kW/hr
Total kW/hr output generator 1 in 1 month	103,878.43 kW/hr
Total kW/hr output generator 2 in 1 month	103,960.37 kW/hr
Total kW/hr output both generators in 1 month	207,838.80 kW/hr

Table 8: Fuel consumption without Solar PV

Fuel consumption by generator 1 in 1 hour	1,436.4 ft^3
Fuel consumption by generator 2 in 1 hour	1,437.0 ft^3
Fuel consumption by generator 1 in 1 month	1,034,208 ft^3
Fuel consumption by generator 2 in 1 month	1,034,640 ft^3
Total Fuel consumption by both generator 1 month	2,068,848 ft^3

Table 9: CO_2 emission without Solar PV

CO_2 emission from generator 1 in 1 hour	173.1 Lbs.
CO_2 emission from generator 2 in 1 hour	173.2 Lbs.
Total CO_2 emission from generator 1 in 1 month	124,654.1 Lbs.
Total CO_2 emission from generator 2 in 1 month	124,752.4 Lbs.
Total CO_2 emission from both generators in 1 month	249,406.6 Lbs.

Table 10: Energy generated by solar PV for one month

Day	Date	Energy in kW/hr	Day	Date	Energy in kW/hr
1	06-24-2014	346.65	16	07-09-2014	361.70
2	06-25-2014	429.75	17	07-10-2014	484.90
3	06-26-2014	338.69	18	07-11-2014	484.92
4	06-27-2014	423.54	19	07-12-2014	489.66
5	06-28-2014	295.73	20	07-13-2014	478.68
6	06-29-2014	478.76	21	07-14-2014	212.05
7	06-30-2014	491.15	22	07-15-2014	431.70
8	07-01-2014	434.42	23	07-16-2014	225.52
9	07-02-2014	302.71	24	07-17-2014	78.96
10	07-03-2014	321.84	25	07-18-2014	160.86
11	07-04-2014	418.42	26	07-19-2014	403.75
12	07-05-2014	468.77	27	07-20-2014	486.18
13	07-06-2014	487.97	28	07-21-2014	465.07
14	07-07-2014	462.65	29	07-22-2014	467.28

15	07-08-2014	374.55	30	07-23-2014	451.25
TOTAL energy generated by Solar PV in 1 month					11,761.13 kW/hr

Table 11: Natural gas generators energy saving with solar PV

Total generator energy used during 1 month period without solar PV	207,838.80 kW/hr
Total generator energy used during 1 month period with solar PV	196,077.66 kW/hr
Total energy savings during one month period	11,761.13 kW/hr

Table 12: Natural gas generators fuel saving with solar PV

Total Fuel Consumption without Solar PV during 1 month period	2,068,848 ft^3.
Total Fuel Consumption with Solar PV during 1 month period	1,961,682 ft^3
Total Fuel Saving during one month period	107,166 ft^3

Table 13: CO_2 emission reduction with solar PV

Total CO_2 emission without Solar PV during 1 month period	249,406.56 Lbs.
Total CO_2 emission with Solar PV during 1 month period	235,293.19 Lbs.
Total CO_2 emission reduction during one month period	14,113.37 Lbs.

Demonstration 4 Conclusion: This demonstration was modified slightly to run the natural gas generators as little as possible. The base had limits on how many hours the generators can be run and they were to run during a power outage only.

However, as soon as the PV inverter was commissioned the PV plant was continuously run. The PV inverter was installed with an energy meter that recorded the power. The generator efficiency was used to estimate the fuel consumption as fuel consumption measurement was not available from generator or facility instrumentation. The test data on the PV was collected for long term and the test data on the generator was collected for short durations and extrapolated. The results show that the:

1. The PV will reduce the energy consumption by 5% if the Chiller were to run 24/7
2. If the Chiller is run during the time when the sun is up (hot period) say 12 hours a day this would be 10%
3. The assumption made was that the chiller runs at full power.

The data collected can be analyzed with different objective function to determine different condition specific results.

6.5 Demonstration 5: PV + Storage support managing variable loads

Purpose: Demonstrate the ability of microgrid compatible PV with storage support to manage variable loads while islanded, without generators online.

Test Sequence:

- Initially, microgrid is operated in grid connected mode.
- The unintentional islanding was initiated - energy storage system and renewables support the microgrid load.

- Load step of 50% of available PV and above 30% PV rated power available are required by success criteria.
- Step change of load during islanded mode, while both generators are off. A series of load steps cycling up and down: 200kW – 100kW – 50kW and so on, the largest individual steps are 100kW. Voltage, Frequency and PV contribution were recorded.

Table 14 below summarizes load changes along with the resulting peak voltage and frequency excursion. At the time these tests were run, PV power was being recorded manually. Hence some measurements are missing as the operator was occupied with executing the manually controlled load steps.

Table 14: Test Data

Time	Load kW	VAC RMS	Avg. Freq (Hz)	PV kW
12:46:00	200.000	500.592	60.019	79.8kW
12:47:46	100.000	491.743	59.932	80.600
12:49:33	50.000	484.392	60.006	80.070
12:51:13	100.000	472.490	59.974	80.400
12:51:17	200.000	458.230	59.974	80.400
12:53:05	50.000	496.103	59.977	
12:55:26	0.000	488.793	60.031	80.200
12:57:20	100.000	461.229	59.981	
12:59:05	200.000	458.576	59.951	80.730
13:01:23	100.000	497.608	59.995	80.900
13:01:25	0.000	498.970	59.995	80.900
13:04:26	50.000	469.388	60.039	81.060
13:05:14	100.000	471.180	59.996	81.060
13:07:08	200.000	468.346	59.944	81.040
13:08:09	150.000	486.996	59.917	81.310
13:08:11	50.000	494.980	60.029	
13:08:13	0.000	491.300	60.029	81.500
13:15:22	100.000	459.729	60.001	81.880
13:16:34	150.000	466.923	59.965	81.790
13:17:32	200.000	477.905	59.924	81.680
13:18:37	100.000	495.263	59.943	
13:18:39	0.000	501.626	59.943	
13:23:05	100.000	460.053	59.991	
13:23:06	200.000	457.202	59.991	82.240
13:23:33	100.000	494.746	59.994	
13:23:34	0.000	498.204	59.994	
13:24:06	100.000	462.680	60.006	

Time	Load kW	VAC RMS	Avg. Freq (Hz)	PV kW
13:25:11	100.000	456.504	59.948	
13:25:13	200.000	455.390	59.948	82.100
13:25:53	100.000	497.941	59.993	
13:25:55	0.000	504.354	59.993	81.720
13:26:28	100.000	463.115	60.032	
13:26:29	200.000	456.066	60.032	81.990
13:26:52	100.000	494.293	60.005	
13:26:54	0.000	500.866	60.005	

The plot (Figure 54) below depicts load steps applied as described above, voltage and frequency axes are set to IEEE 1547 limits.

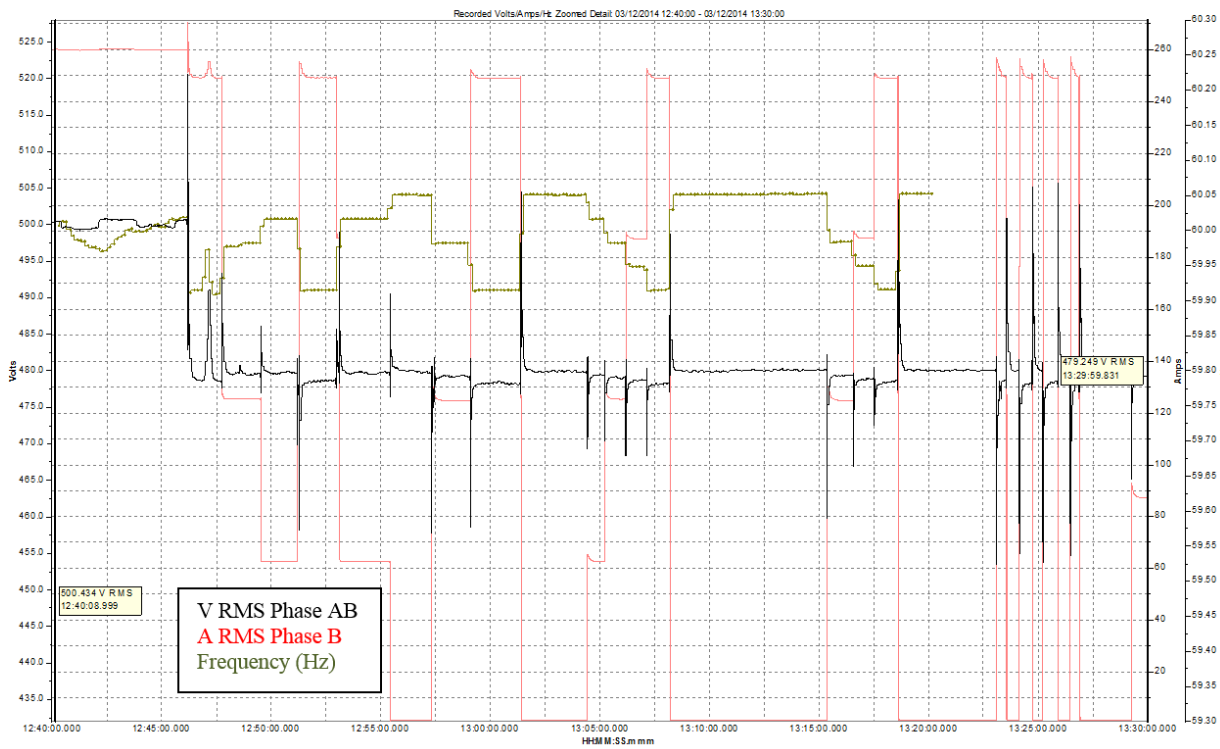

Figure 54: PV + Storage support managing variable loads – Islanded, generators disabled

Demonstration 5 Conclusion:

The microgrid's total PV rating is 104kW (PV1 + PV2) and on the day of this test – March 12, 2014 - the available PV was an estimated 85kW. Therefore, 100kW load steps applied during the test were greater than both of the load step levels required by the success criteria for this objective: 50% load step for rated PV and the 30% for the available PV. The combination of PV and energy storage maintained PQ within IEEE 1547 limits without generators, further, it should be noted at the time of the test the battery was at less than full capacity as described previously.

6.6 Demonstration 6: PV + Storage support managing variable solar

Purpose: Demonstrate the ability of microgrid compatible PV with storage support to manage variable solar (available power) while islanded, without generators online. Typical PV inverters go offline when the utility is not present. A PV inverter, combined with storage inverter support and microgrid controls, can power a microgrid without generators, given variable PV power and power demand within the PV available output capacity.

Success Criteria: In a solar day with the load less than 50% of average available PV, microgrid bus will remain stable, with no generators on line. Stable bus is defined as voltage maintained within +10%/-12%, and frequency within 60.3Hz/59.3Hz. The 50% level is selected based on power (and not energy) optimized battery.

Test Sequence:
Alternative Test Procedure Performed:
Due to clear, full sun conditions, PV output was manually changed.

- A 70kW (~86.5A/phase) resistive load was set, driven by the PV (~80kW) online and storage.
- The load level was maintained throughout the test.
- Available PV was adjusted by closing or opening 2 of the 3 PV system combiner boxes. Each combiner controls about 1/3 of the available PV (1/3 of the 86kW array).
- Adjustments to the level of available PV were made each minute over a period of 15 minutes (Variable PV).

Table 15: Test Data

Minutes	Frequency (Hz)	PV Output (kW)	VRMS (BC)
0	60.003	81	479.5
1	60.002	80.9	479.5
2	59.984	53.2	479.5
3	59.966	26.2	479.5
4	59.984	52.26	479.5
5	60.002	80.5	479.5
6	59.966	26.32	479.1
7	59.963	24.06	479.1
8	59.964	33.02	479.1
9	59.985	54.32	479.1
10	60.003	80.38	479.1
11	59.985	54	479.1
12	59.968	26.32	479.1
13	60.001	53.68	479.1
14	59.98	26.01	479.1
15	59.949	0	479.1

Table 15 above indicates that although the PV is experiencing large step changes in output, voltage and frequency are supported by the energy storage and are essentially flat over the course of the test and within IEEE 1547 limits. The plot of this test, Figure 55 depicts the change in frequency relative to PV output changes.

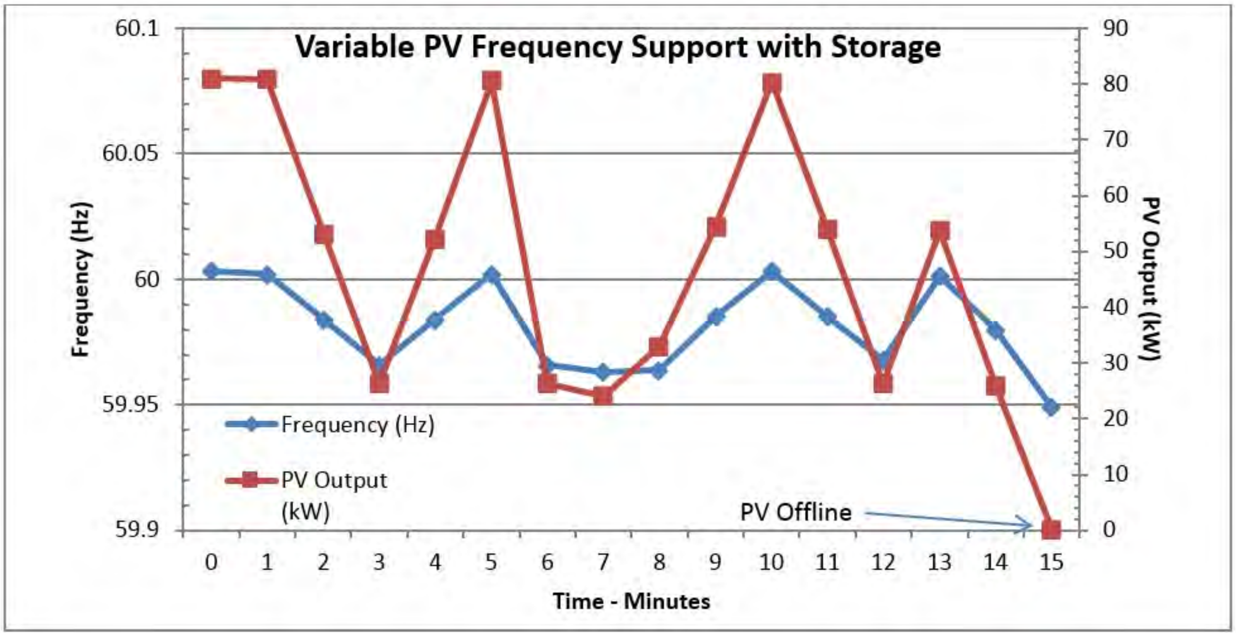

Figure 55: Variable PV Frequency Support with Storage

Table 16 below illustrates PV charging of batteries when microgrid load requirements are met.

Table 16: PV Charging of Batteries

ToD	V RMS	A RMS	Freq	Battery Pack	Battery Pack	PV Output (kW)	# COMBINERS
	BC	**B**	**Avg. (Hz)**	**% SOC A**	**% SOC B**	**(Contribution)**	**Connected**
13:34	479.5	86.76	60.003	80	75	81	3
13:35	479.5	86.76	60.002	79	74	80.9	3
13:36	479.5	86.76	59.984	78	73	53.2	2
13:37	479.5	86.76	59.966	77	71	26.2	1
13:38	479.5	86.76	59.984	76	70	52.26	2
13:39	479.5	86.76	60.002	76	69	80.5	3
13:40	479.5	86.76	59.966	75	67	26.32	1
13:41	479.1	86.76	59.963	73	64	24.06	1
13:42	479.1	86.76	59.964	71	61	33.02	1
13:43	479.1	86.76	59.985	70	60	54.32	2
13:44	479.1	86.76	60.003	71	60	80.38	3
13:45	479.1	86.76	59.985	69	58	54	2

13:46	479.1	86.76	59.968	68	56	26.32	1
13:47	479.1	86.76	60.001	67	54	53.68	2
13:48	479.1	86.76	59.98	65	52	26.01	1
13:49	479.1	86.76	59.949			0	0

Figure 56 below plots % SOC verses PV output with a consistent 70kW load.

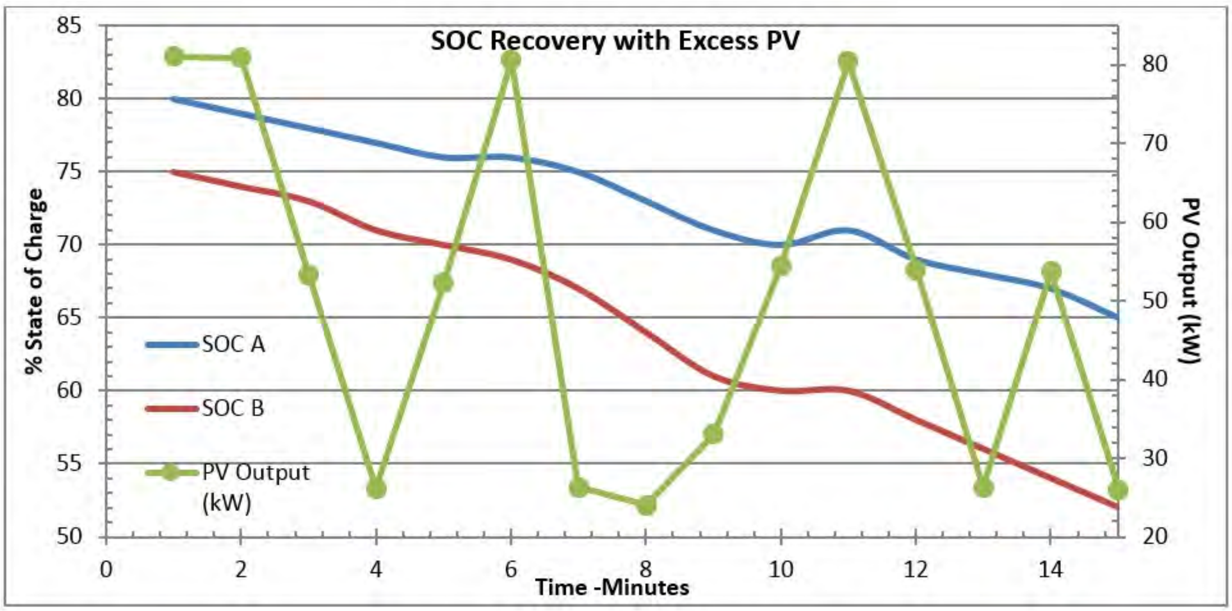

Figure 56: Greater PV output allows SOC to recover or slows SOC decline

Figure 56 above demonstrates the reduced capacity of Battery Pack B: a higher rate of decline in SOC as well as a lower % SOC starting point when compared with Pack A. It also shows battery charging (SOC increasing) when PV power is greater than connected load (of 70kW).

Additional test for variable solar under constant load:
Variable Solar due to setting sun – Load: 25kW resistive plus “Sweep” Pump (40hp) Figure 57 below:

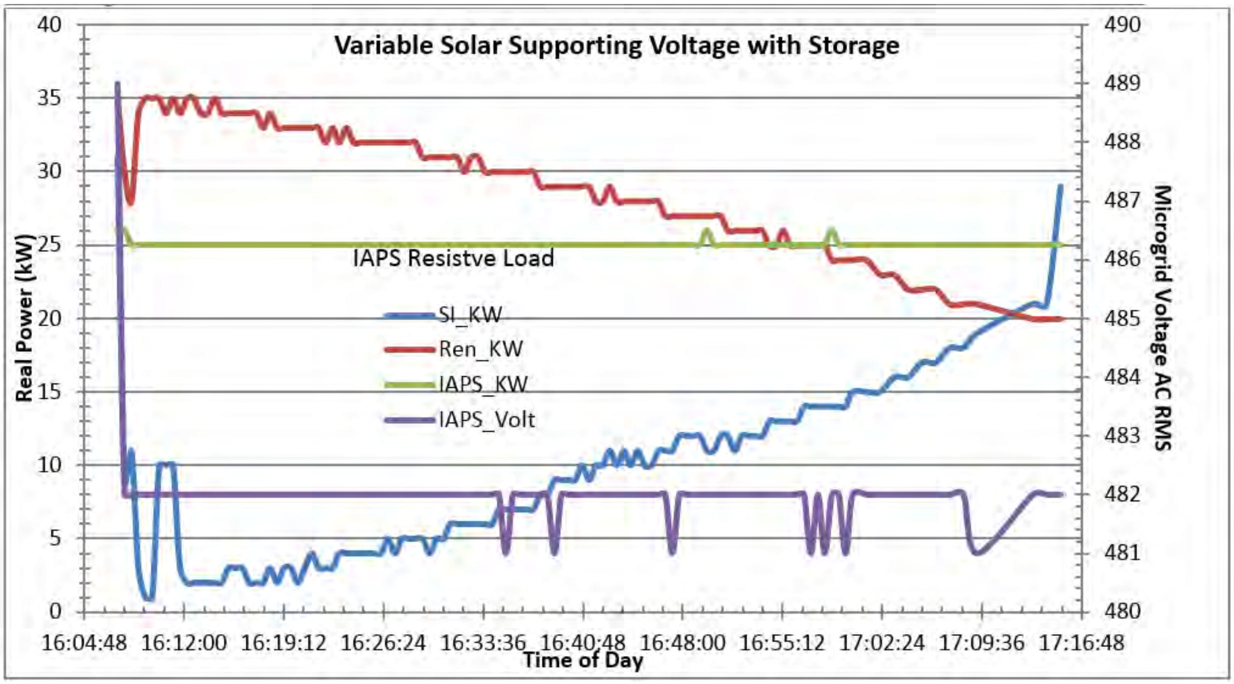

Figure 57: Voltage and Frequency Support with PV Curtailment (Full Capacity Battery)

Note that SI and PV inverter controls curtail PV output to avoid over charge of battery when microgrid is islanded and PV production is in excess of microgrid load and battery charging needs (i.e. high SOC).

Figure 58 below – Frequency support during the same variable solar test (within IEEE 1547 limits):

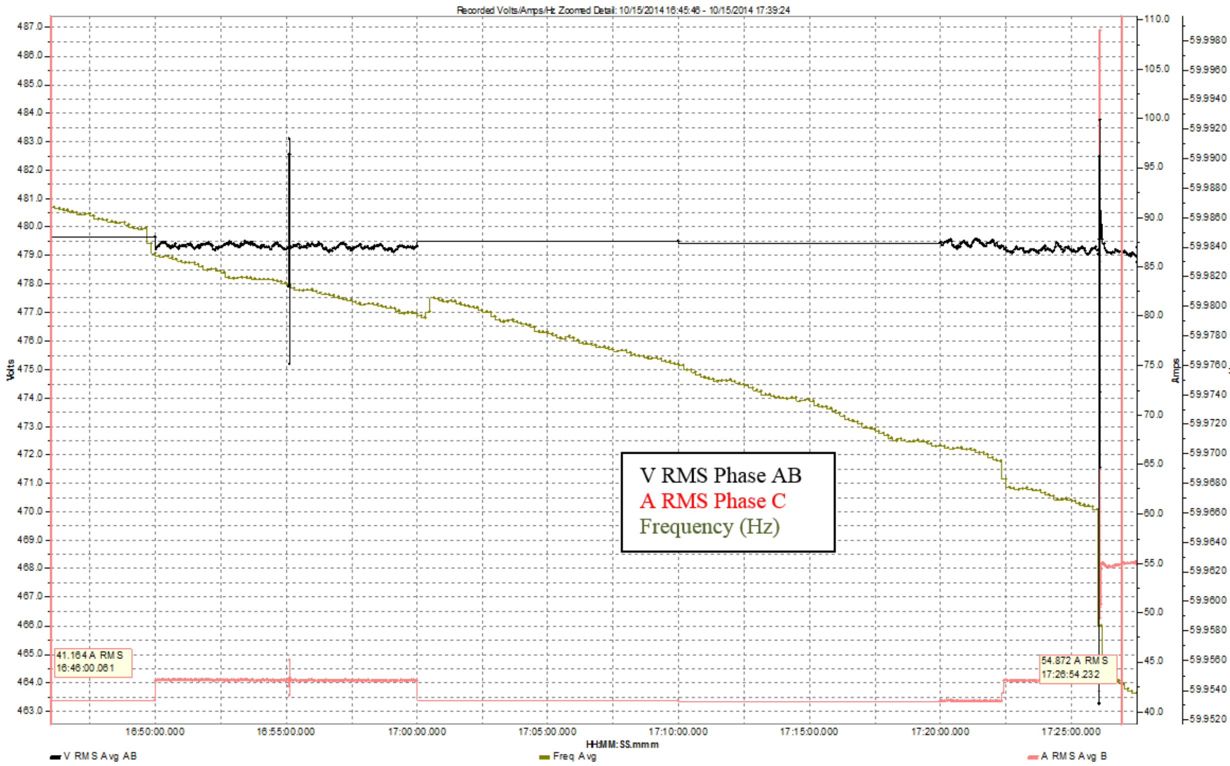

Figure 58: "End of Day" Scenario: Bus Voltage, Current and Frequency (Slow Varying PV)

Demonstration 6 Conclusion: The performance of the microgrid when the renewables and the energy storage alone are present: when the load conditions are light, the energy storage and renewables inverter can support the loads. The load could be larger than the renewables or the load can be smaller. Also, the renewables are intermittent and the energy storage inverter is shown operate the microgrid stably. The test demonstrates the conditions where clouds intermittently cover and clear over the array. In addition, an end of the day scenario when the PV irradiation drops was demonstrated. The SI controls and the PV inverter controls are designed such that:

1. The SI can charge or discharge the battery to maintain a load-source balance.
2. The renewable smart inverter has a curtailment control that depends on the SOC of the battery.
3. The storage inverter is the master.
4. The renewable inverter is not designed to operate in an island for safety purposes and so it never supports the grid on its own.

6.7 Demonstration 7: Procurement cost reduction of storage

Purpose: Demonstrate that a significant equipment cost reduction can be achieved by using power optimized storage. The energy storage components in military microgrids are typically the highest cost parts of the system. Reduced cost may enable wider acceptance of microgrid in the DoD.

Success Criteria: A 67% reduction of procurement cost of storage system for the new power optimized storage versus the existing energy based storage system (flow battery) at the Fort Sill microgrid.

Test Sequence: Create a table comparing the procurement costs of the battery products employed.

The original microgrid at Fort Sill featured an energy optimized storage system. This was a 500kVA continuously rated inverter, and a ZBB flow battery system rated for 250kW for 2 hours (and 400kW for 3 minutes). (Note: The ZBB energy storage at Fort Sill was actually leased for the project and not purchased due to the high capital costs and development nature of the project).

The power optimized storage system costs are based upon data from Altairnano, supplier of the Li-Ion system installed at Fort Sill for this demonstration project and the inverter design considerations described below.

Transient Rated Inverter Design Considerations:
The power rating of the inverter is based on the power device's operating junction temperature. Typical air cooled inverters for continuous operation are designed for 125^{O}C junction temperature and a heat sink temperature of 85^{O}C. However, the IGBT's can safely operate up to 150^{O}C junction temperature. So the heat sink temperature can exceed 85^{O}C for a short time. The over current rating is based on this margin available. The cost reduction of the transient inverter will be based on the one minute over-current rating of the inverter and a cooling system that will remove heat and maintain the heat sink below 85^{O}C. Figure 59 below shows the heat sink temperature rise with time at full power on a typical inverter. With adequate cooling the inverter can meet short overloads. Hence a 125kW inverter can be used as a 187kW transient inverter by enhancing the cooling and ensuring the heat sink temperature is well controlled.

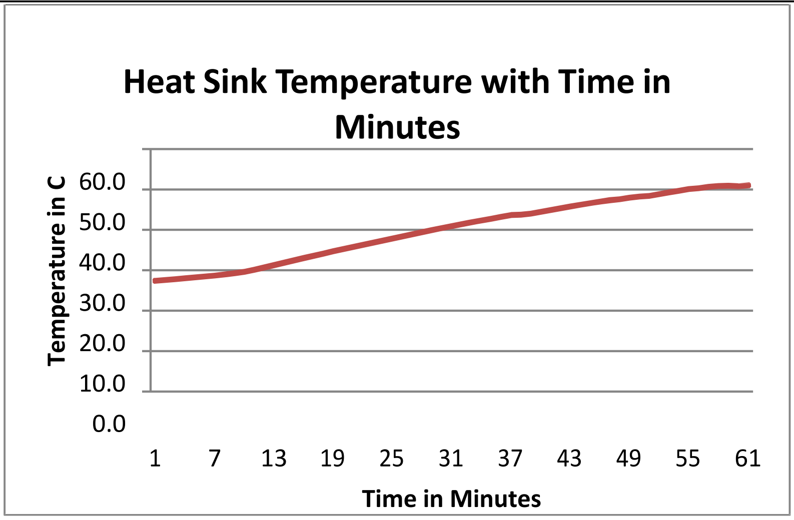

Figure 59: Relatively Long Period Heating Allows For Smaller Transient Inverter

Test Data:

Table 17: Cost Comparison of Stoarge and Inverter Systems

Cost Comparison of Storage and Inverter Systems			
	Storage System	**Inverter**	**Total**
Energy Optimized Flow Battery Storage	$480,000	$120,000	$600,000
Power Optimized Storage with Transient Inverter	$118,000	$80,000	$198,000
Per Cent Procurement Cost Reduction	75.4	66.7	67.0

Demonstration 7 Conclusion:

Table 17 above indicates that the 67% cost reduction can be achieved by virtue of using a physically smaller, power optimized battery. Along with the smaller battery come other procurement cost saving benefits such as smaller inverters, less installation infrastructure (concrete pad, mounting hardware, etc.) reduced installation costs and possibly shorter conductor lengths. The power optimized storage system cost shown above is based on production quantities. The transient rated inverter cost is an estimate based on an available Eaton production PV inverter of appropriate rating.

6.8 Demonstration 8: Smaller Footprint for Storage

Purpose:
Having a smaller equipment footprint benefits the site by allowing for more flexibility in installation location selection, including indoors, lower installation costs, and enabling simpler portability (if needed).

Success Criteria:
A 50% reduction of storage system footprint for the new power optimized storage versus the existing energy based storage system (flow battery) at the Fort Sill microgrid.

Test Sequence:
Create a table comparing physical area and volume of the battery products employed.

Data:
Energy Optimized Flow Battery Storage – Square Area Footprint and Cubic Volume. This is the original ZBB flow battery system installed at Fort Sill.

Figure 60: ZBB Flow Battery

Data:
Power Optimized Storage (Li-Ion) – Square Area Footprint and Cubic Volume. This is the new Altairnano Li-Ion based storage system installed at Fort Sill.

Figure 61: Altairnano Battery Packs

Analysis:

Table 18: Area & Volume Comparison of Storage Systems

Area & Volume Comparison of Storage Systems				
	Power	**kWh**	**Footprint**	**Volume**
Energy Optimized Flow Battery Storage	250 kW 400 kW for 3 min	500	132ft²	1056ft³
Power Optimized Storage (Li-Ion)	400 kW	56	17ft²	112ft³

Demonstration 8 Conclusion:
The power optimized storage system requires only 12.8% of the volume of the flow battery used for a previous project. The battery system (power optimized) used for this project clearly exceeds the 50% storage system footprint size reduction criteria verses the energy optimized system.

This smaller physical size increases the possibility of locating the battery indoors in cases where building space is at a premium.

6.9 Demonstration 9: Ramp rate control of PV power transitions with support from energy storage.

Purpose:
Demonstrate the ability of the combined PV and storage to ramp the “effective” power down during a PV power reduction event (i.e. a cloud passing overhead) which can cause grid instabilities when the PV is a high penetration of local power. Storage can be used to mitigate the effect of rapid PV power reductions by having the power down ramp rather than a step.

Test Sequence:
Recorded system electrical parameters were examined to determine if rapid reduction of PV output has an effect on utility PQ. Result was that changes in available PV contribution are not large enough to cause disturbances that are outside of IEEE 1547 limits. Hence storage will not engage transition support.

Test Data:
Sample 1: A PV power decrease of 54kW over 44 seconds has negligible effect on utility PQ, plotted Figure 6262. System is driving an ambient load of ~110kW.

Table 19: Demo 9; Sample 1

Time	Ren_KW	Util_KW	Util_Volt	Util_Freq
13:21:16	66	31	478	6000
13:21:18	67	29	478	6001
13:21:20	66	31	478	6001
13:21:22	62	34	478	6001
13:21:24	55	47	478	6000
13:21:26	48	57	478	6000
13:21:28	39	68	478	6000
13:21:30	27	83	478	6000
13:21:32	21	92	477	6001
13:21:34	19	93	477	6000
13:21:36	21	92	477	6001
13:21:38	18	94	477	6001
13:21:40	16	99	477	6001
13:21:42	15	99	477	6000
13:21:44	15	99	477	6000
13:21:46	14	99	477	6001
13:21:48	14	100	477	6000
13:21:50	14	102	477	6000
13:21:52	14	102	477	6000
13:21:54	14	101	477	6000
13:21:56	14	100	477	6000
13:21:58	13	101	478	6000
13:22:00	13	100	477	6000

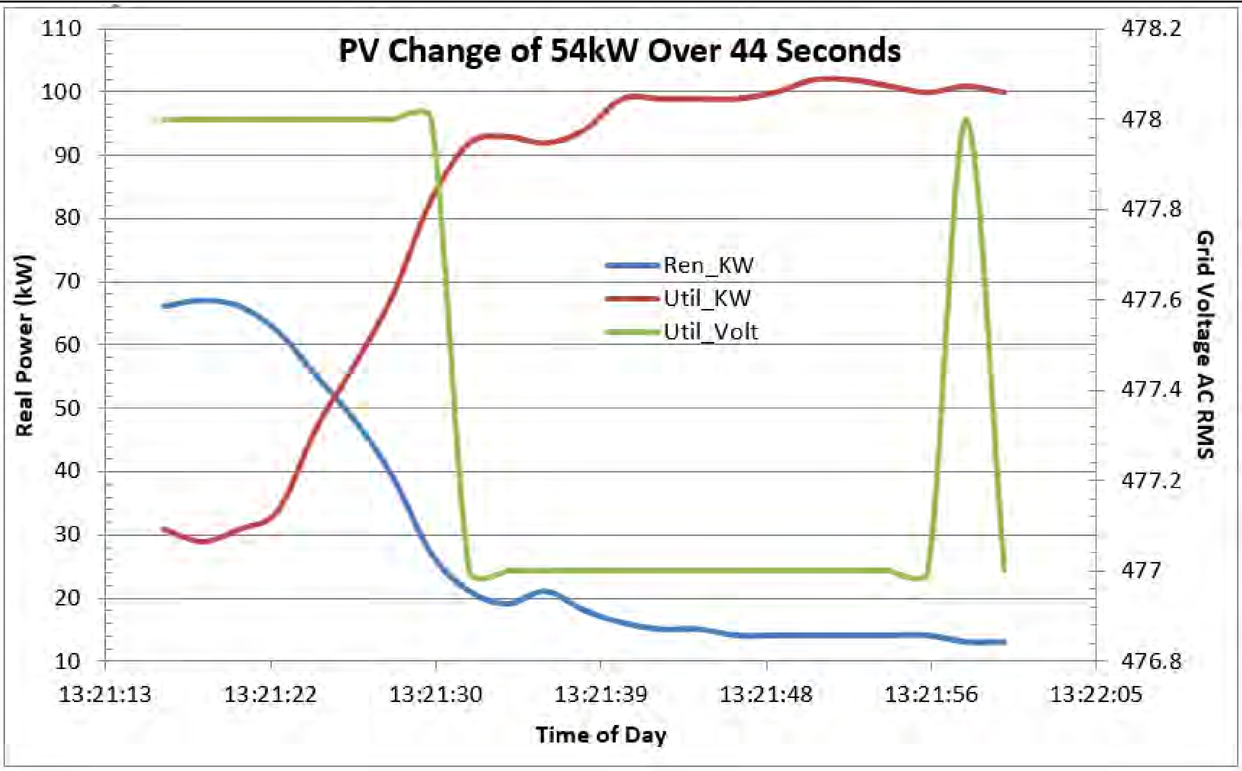

Figure 62: PV reduction causes one volt deviation in Utility

Test Data:
Sample 2: A PV power decrease step of 34kW over 4 seconds has negligible effect on utility PQ – Table 20, plotted Figure 6363. System is driving an ambient load of ~40kW.

Table 20: Demo 9; Sample 2

Time	Ren_KW	Util_KW	Util_Volt	Util_Freq
15:31:38	40	-30	488	6001
15:31:40	41	-30	488	6000
15:31:42	41	-31	488	6000
15:31:44	41	-31	488	6000
15:31:46	41	-31	488	6000
15:31:48	41	-31	488	6000
15:31:50	39	-28	488	6000
15:31:52	7	14	485	6000
15:31:54	4	16	485	6000
15:31:56	9	10	485	6000
15:31:58	9	10	486	6000
15:32:00	9	10	486	6000

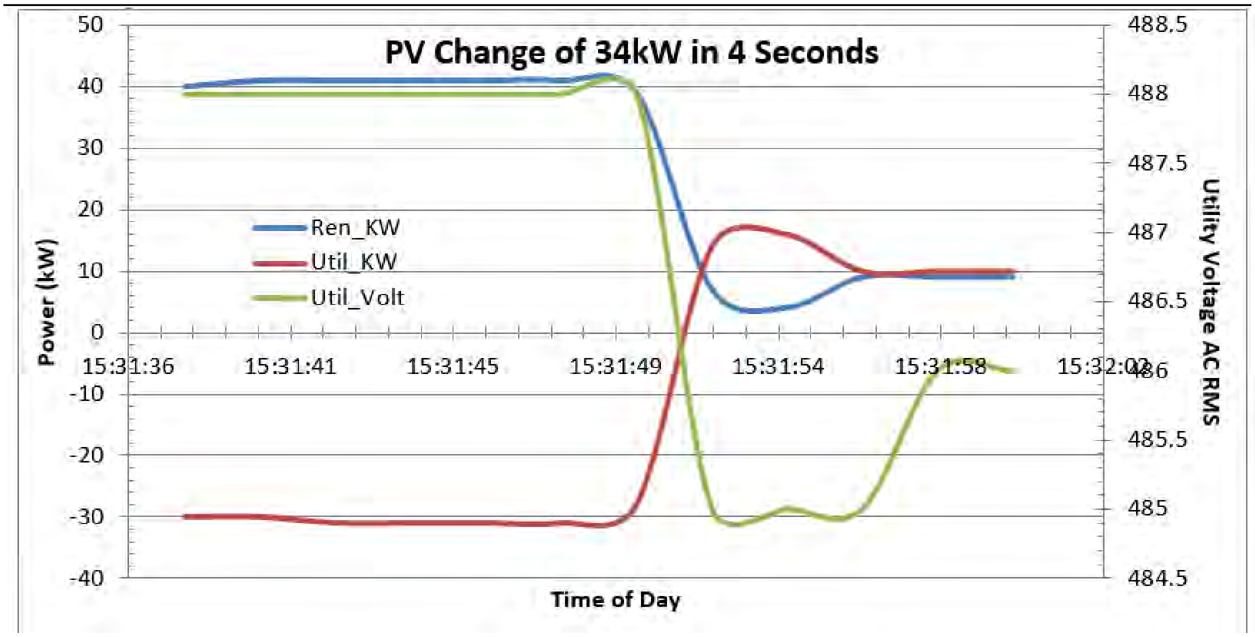

Figure 63: Utility 3 Volt Deviation Due to PV Decrease

Test Data:

Sample 3: A PV power decrease step of 43kW over 2 seconds has negligible effect on utility PQ – Table 21, plotted: Figure 6464. System is driving the chiller load of ~270kW.

Table 21: Demo 9; Sample 3

Time	Ren_KW	Util_KW	Util_Volt	Util_Freq
15:25:52	50	209	481	6000
15:25:54	50	209	481	6000
15:25:56	50	210	481	6000
15:25:58	50	210	481	6000
15:26:00	7	266	480	6000
15:26:02	7	267	480	6000
15:26:04	7	268	480	5999
15:26:06	7	267	480	6000

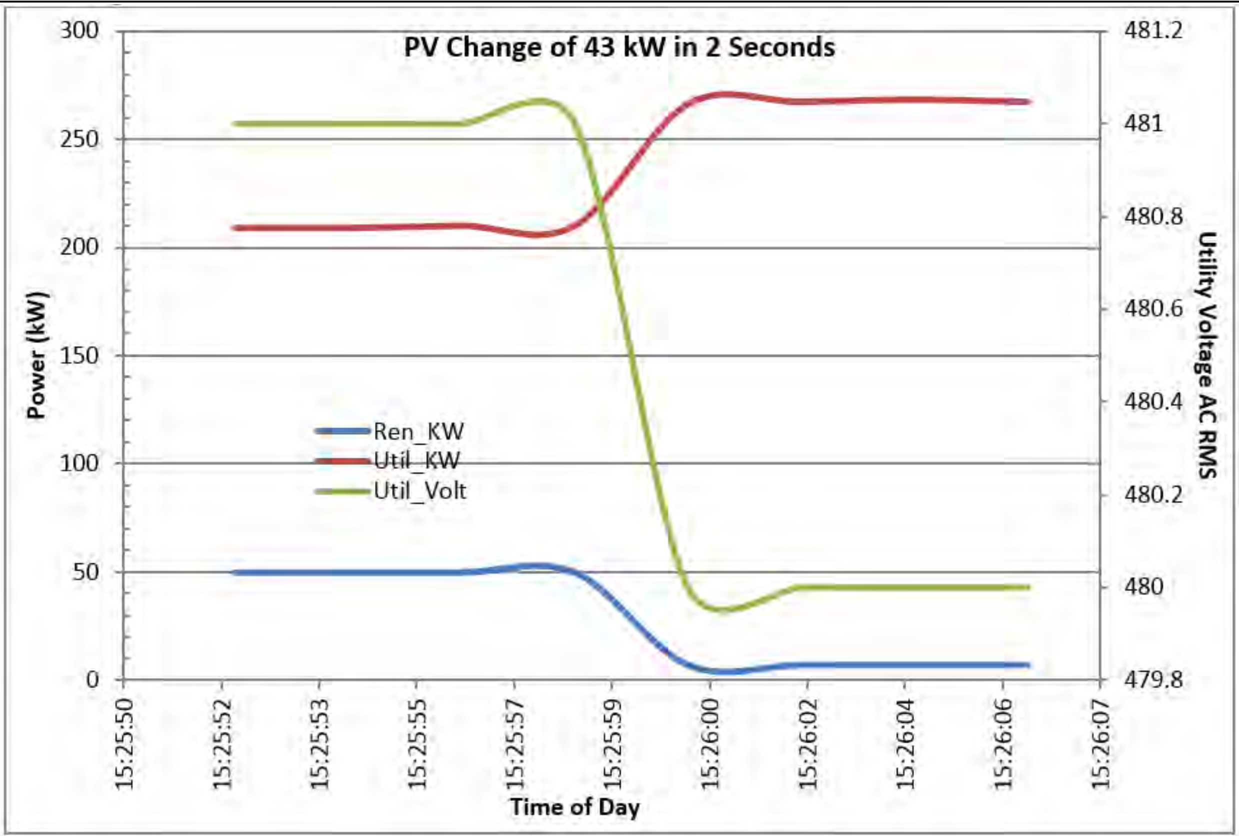

Figure 64: Minimal voltage deviation due to PV change in a heavily loaded microgrid

Demonstration 9 Conclusion:
PV ramp rate control was not demonstrable as PV penetration is not sufficient to have power quality impact on the utility grid at the Ft Sill location, as the grid is too "stiff". Changes in available PV contribution are not large enough to cause out of IEEE 1547 limit disturbances. Storage will not engage transition support.

6.10 Demonstration 10: High penetration PV and control of PV power ramp rate for generator stability.

Purpose:
Demonstrate the ability of the storage system to maintain a stable islanded microgrid bus during PV power steps (by ramping total power), when islanded with generators and PV sources. Solar irradiation steps can result in microgrid instabilities, given generator and high penetration PV sources (approximately 18% in this microgrid). By using storage to ramp power (up or down to the final value as needed) over a longer time, the generator output is stabilized resulting in a stable microgrid bus.

Test Sequence:

- Microgrid is operated in island mode and is loaded with 100 kW of resistive load.
- Generator 1 is ON, Generator 2 is disabled
- A rapid PV power reduction event is created by manually turning on and off the solar PV strings at the array combiner boxes.
- The energy storage inverter is maintaining the ramp rate by providing support to rapid PV power fluctuation.
- Red Lion records CAT_ISO measurements of voltage, frequency and active power output energy storage, Generator 1 and Solar PV. The Fluke 1750 makes voltage and current measurements in parallel

Test Data:

Energy storage inverter provides PV ramp rate support and maintaining the system voltage and frequency and avoiding instability issues caused by solar PV intermittency.

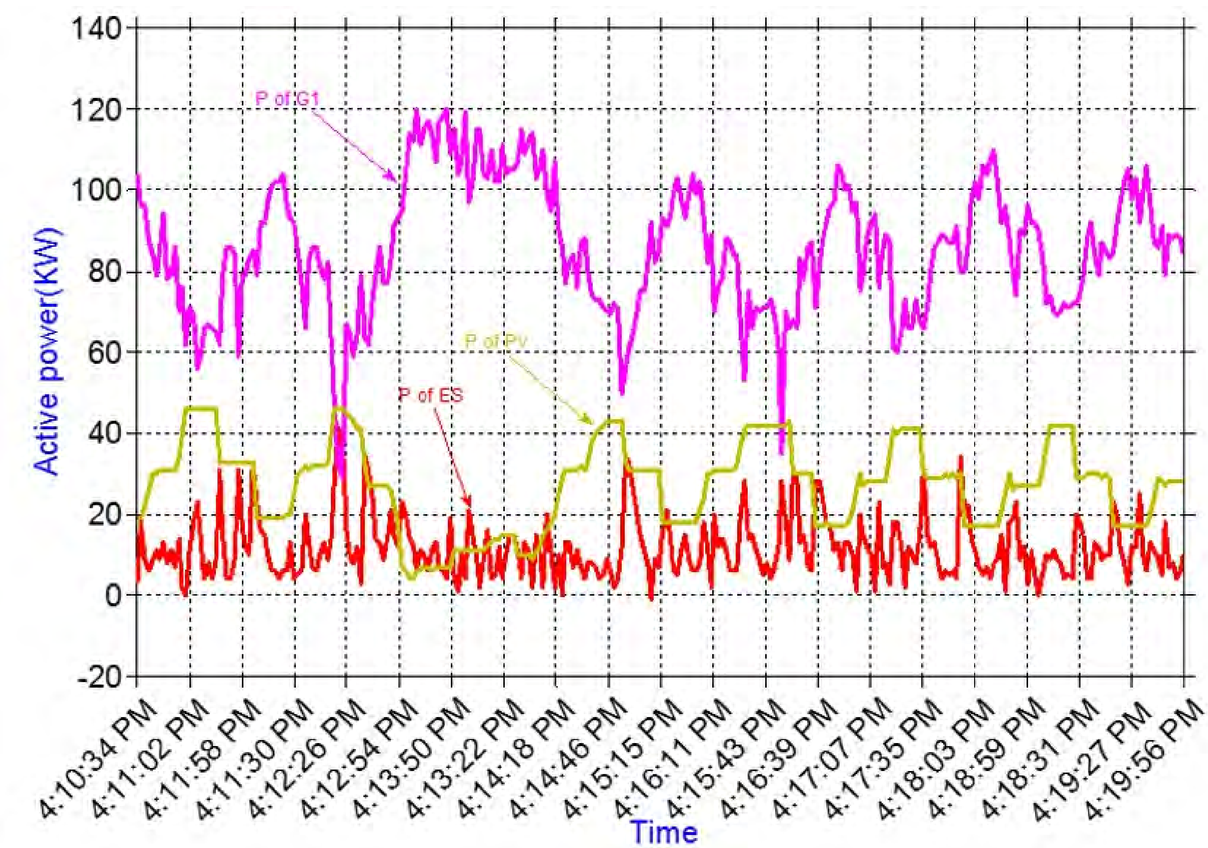

Figure 65: Active Power of utility, energy storage inverter, generator 1 and renewables; ramp rate control of PV power

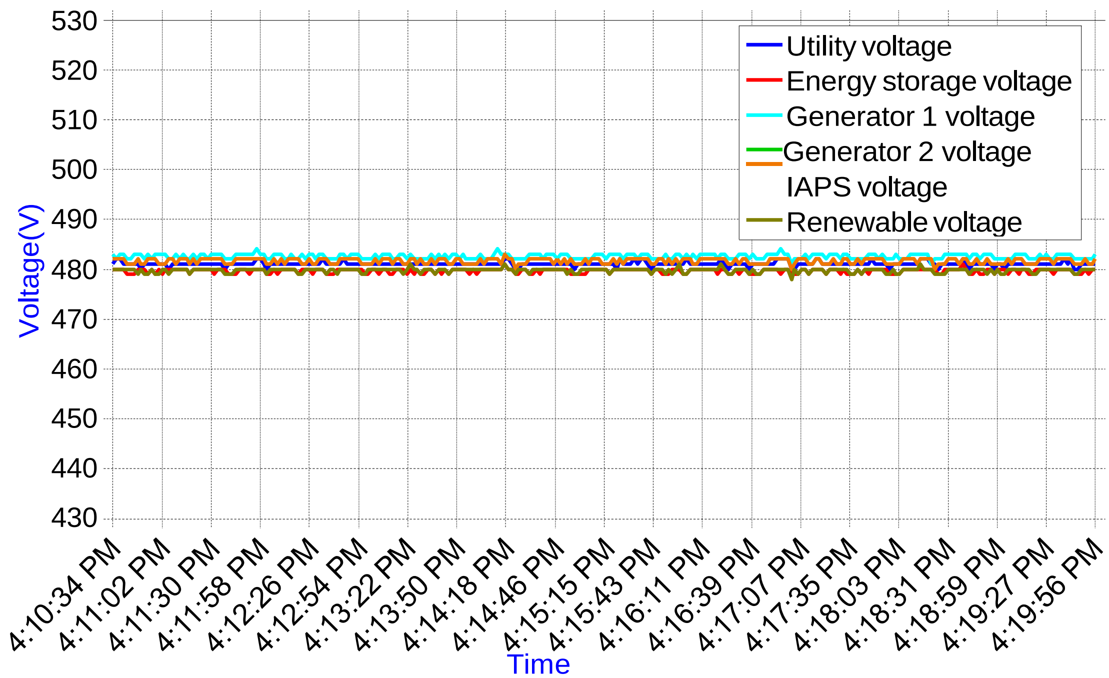

Figure 66: RMS voltage at utility, energy storage inverter, Generator 1, Generator 2 and renewables; ramp rate control of PV power transition with support of energy storage system.

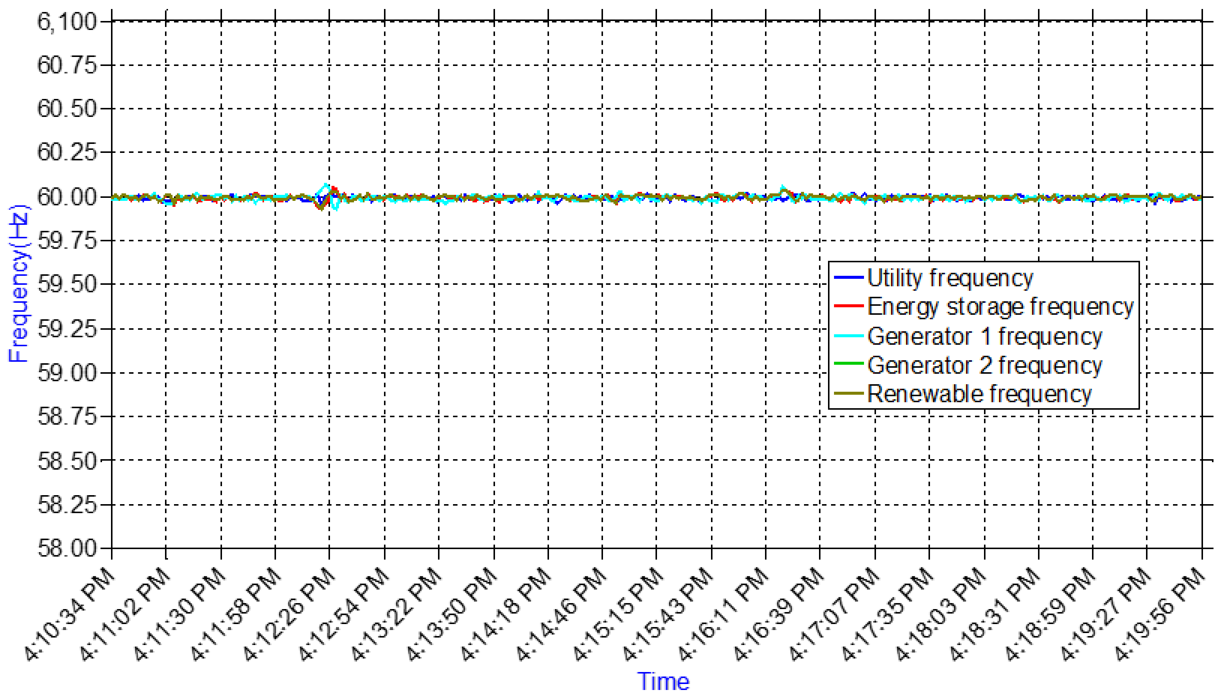

Figure 67: Frequency measured at utility, energy storage inverter, Generator 1, Generator 2 and renewables; ramp rate control of PV power transition with support of energy storage system.

Demonstration 10 Conclusion:
The data presented for demonstration 10 plus the results of demonstrations 5 and 6 show that with energy storage, power quality of the microgrid can be generally maintained within IEEE 1547 limits in the presence of sudden load or PV power contribution changes.

6.11 Demonstration 11: Microgrid voltage support from PV inverter

Purpose:
The PV inverter can supply kVARs to support microgrid voltage during load steps independent of the PV power available. During typical usage the full kVA capacity of PV inverters is not utilized for delivering PV power (as solar illumination may be limited). Typically 50% of the capacity is available. This inverter capacity can be used for grid support, given integration with the microgrid control system.

Note on kVAR levels: The central PV inverter for the 86kW solar array is rated at 250kW, and is made up of two separate (parallel connected) 125kW inverters. This array installation is using only one of these inverters, as the PV inverter automatically disables one inverter for less than 125kW operation. The success criteria for demonstration 11 states that the PV inverter will provide 125kVAR. However, tests were run at 90kVAR. When modifying the PV inverter controls it was discovered that a single inverter cannot produce kVAR at its rated level when the DC input is limited to 86kW. Therefore, the tests were run at the highest kVAR level possible given the limitation.

Test Sequence:

- The controls of the central PV inverter of the 86kW solar array (PV2) were modified to allow the inverter to source 90kVAR continuously regardless of actual PV kW output
- Islanded microgrid operations were executed with Chiller #3 as the load, these operations included chiller starts
- The data recorded, particularly the chiller starts, will be compared with earlier chiller starts where the added kVAR support was not provided

Test Data: Plotted, Table 22 and Figure 68 shown below:

Table 22: Demo 11 Test Data

Time	G1_KVAR	G2_KVAR	SI_KVAR	Ren_KVAR	SI_Volt
11:08:46	-3	1	-56	89	480
11:08:48	127	124	245	81	440
11:08:50	112	129	214	86	461
11:08:52	6	32	8	90	480
11:08:54	-19	-36	104	90	489
11:08:56	-35	-48	128	88	480
11:08:58	-42	-48	132	88	479
11:09:00	-49	-41	134	88	478
11:09:02	-53	-39	131	88	479
11:09:04	-37	-39	124	88	481
11:09:06	-36	-37	119	88	481
11:09:08	-33	-29	117	88	481
11:09:10	-29	-26	99	88	482
11:09:12	-24	-16	89	88	481
11:09:14	-14	-16	77	88	484
11:09:16	-11	-13	74	88	482
11:09:18	-9	-6	61	88	482

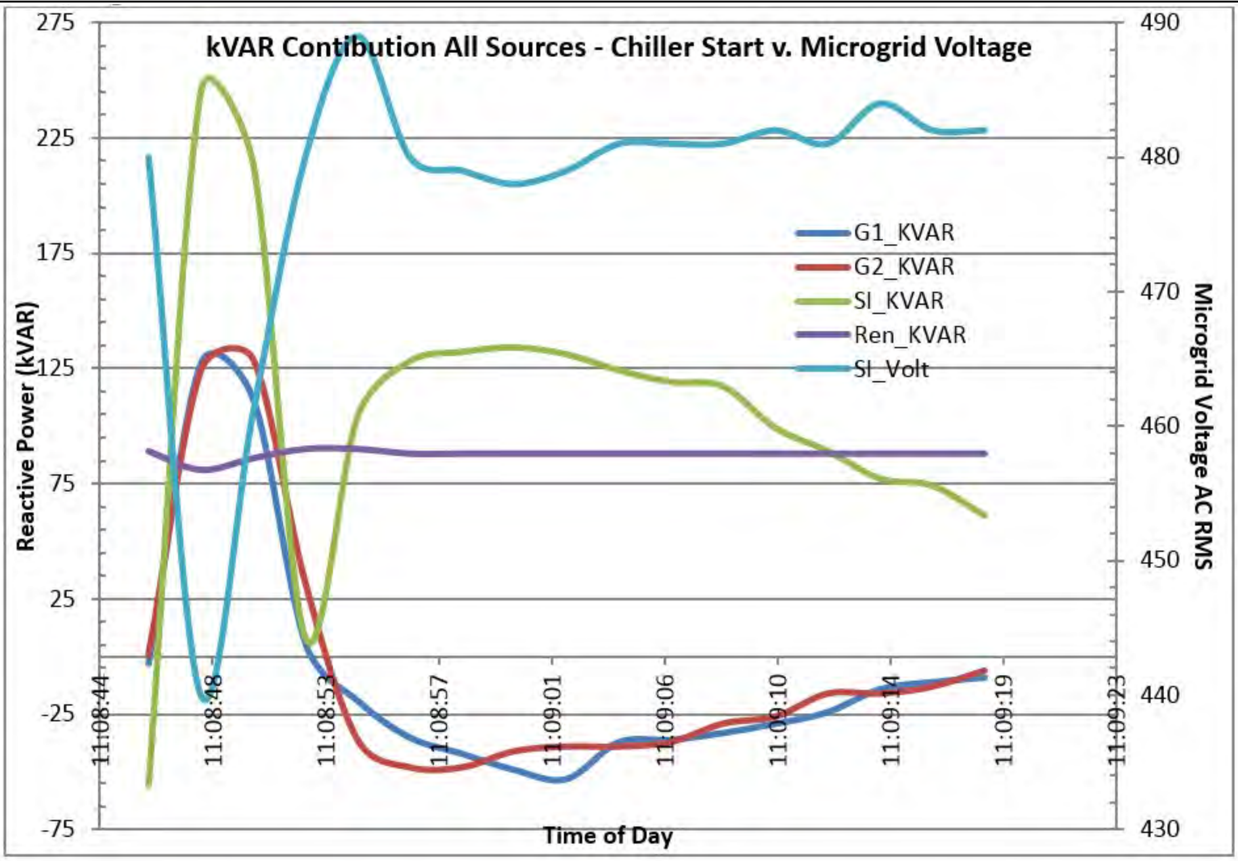

Figure 68: Continuous kVAR support from the PV inverter

Although the chart and table above indicate a minor disturbance of the microgrid voltage during the chiller start, this start was recorded as a PQ "event" by the Fluke 1750 recorder. Even though this is a PQ event, it was much less severe than other recorded starts that did not have the additional kVAR support. This can be seen in comparing the plots of three different chiller starts:

1. Generator only start (the two NG generators are the only power sources used to perform the start)
2. Full microgrid system (all sources)
3. Full system start with the additional kVAR provided by the PV inverter.

"Generator only" Chiller Start (the two NG generators are the only power sources used to perform the start):

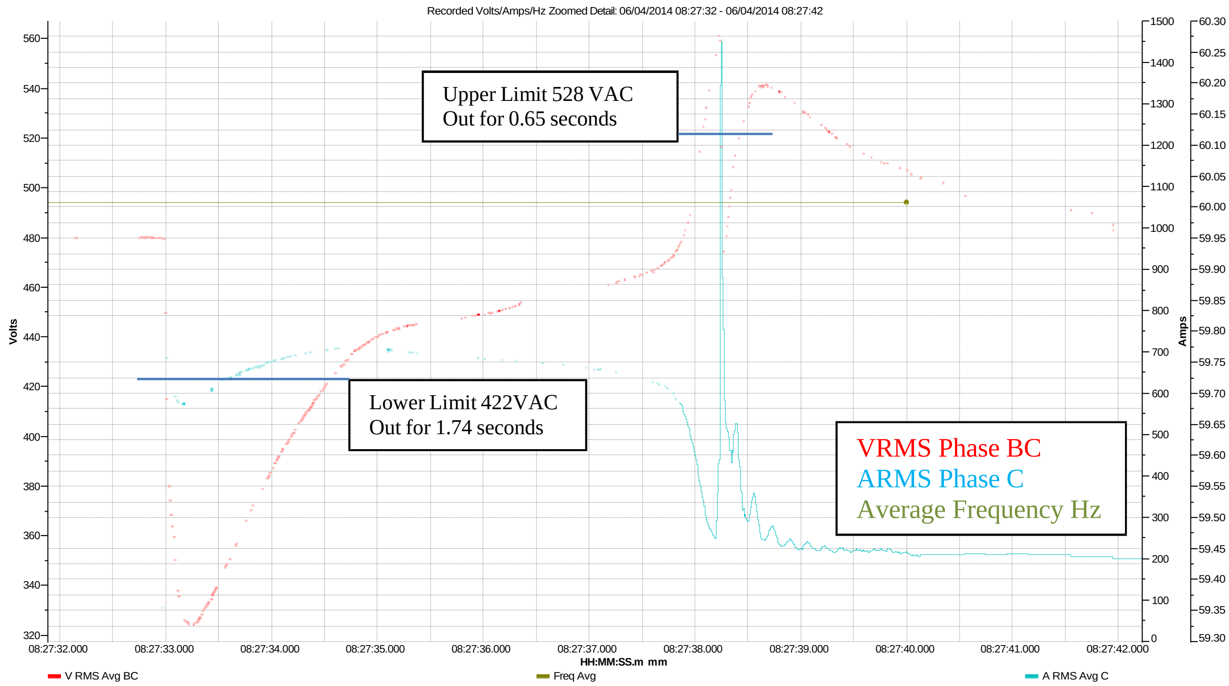

Figure 69: "Generator Only" Start: Both Upper and Lower Voltage Limitations are Exceeded

Full Microgrid Chiller Start:

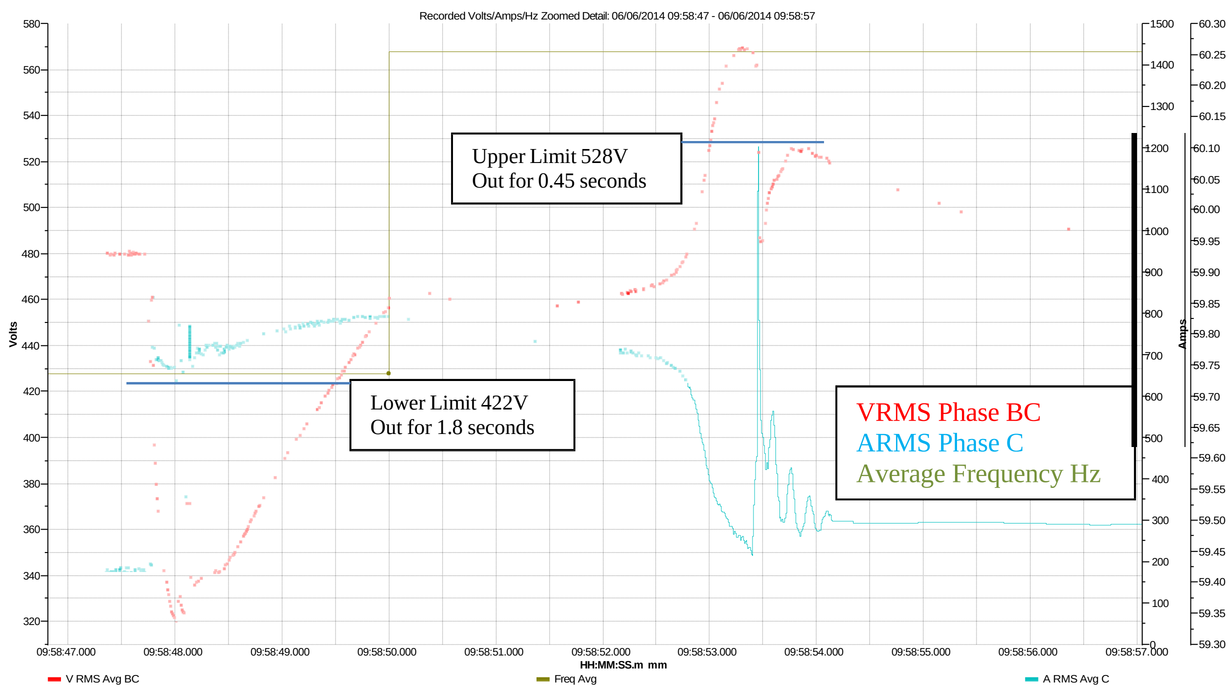

Figure 70: Full Microgrid (all sources) Start: Both Upper and Lower Voltage Limitations are Exceeded

Full Microgrid Chiller Start with Added kVAR Support:

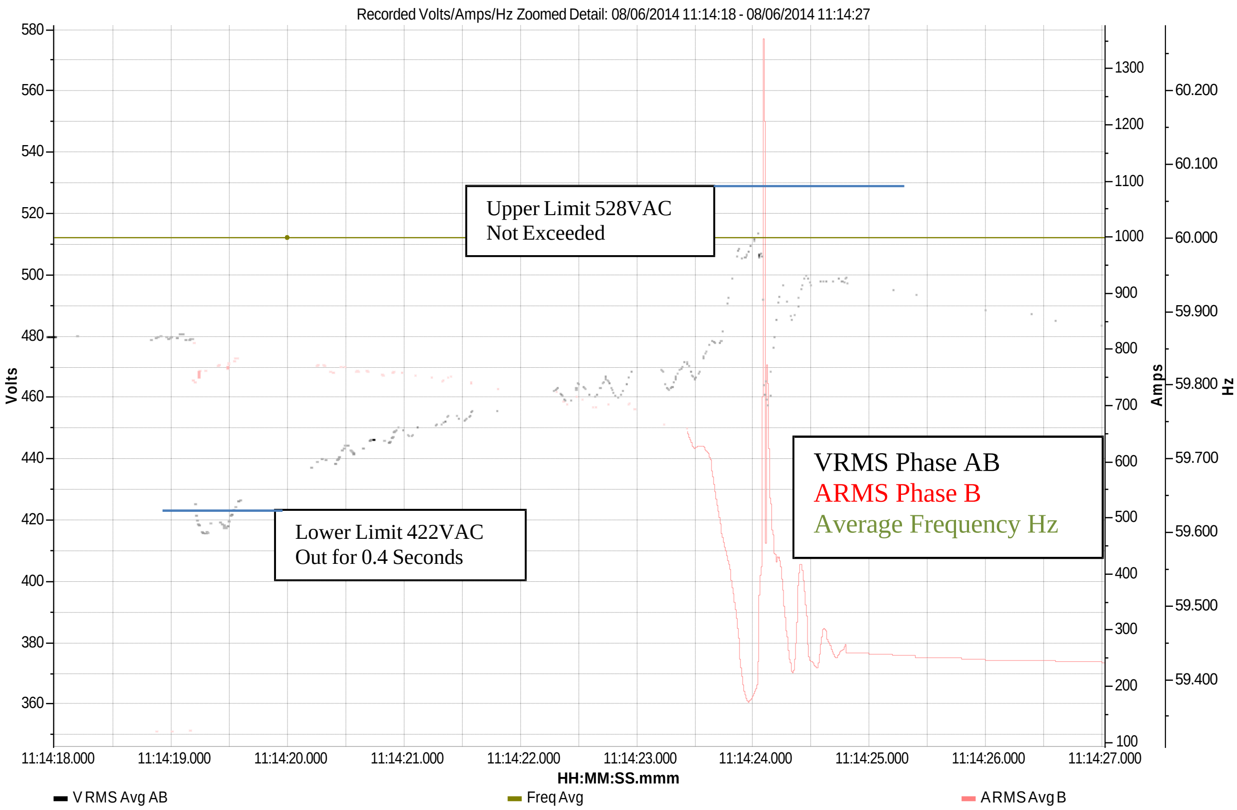

Figure 71: Full Microgrid With PV kVAR Support: Only the Lower Voltage Limit is Exceeded

Demonstration 11 Conclusion:

It can be observed from the plots above that the 90kVAR reactive power contribution from the PV inverter effects PQ positively when the microgrid is handling a large reactive load step, nearly bringing the starting event into IEEE1547 compliance. As stated earlier in this report, using a reduced voltage motor starter to start the chiller would allow “clean” starts whether the system was islanded or not.

Another benefit of the added reactive power support is optimizing power quality by reducing line losses. Note that in the photograph (Figure 68) of the HMI, the “pf” – Power Factor values for the generators and the utility are at or near unity (1.00) and the kVAR value for the Storage Inverter and Renewables (PV); all are circled.

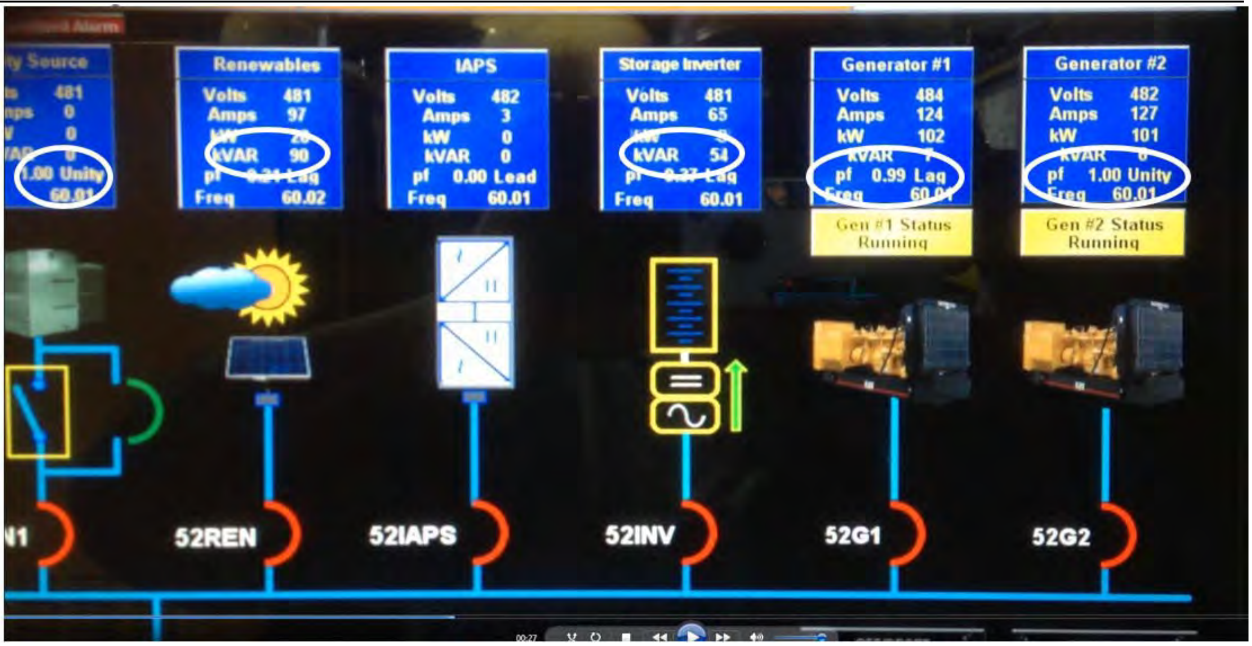

Figure 72: Power Factors and kVAR value with reactive power support

6.12 Demonstration 12: Validate/Quantify storage needs – peak power and time duration

Purpose:
Determine if the selected power optimized storage is of sufficient size for the Fort Sill microgrid system, for facilitating non-disruptive islanding transitions, supporting transient load steps up and riding through brief power quality events.

Peak power demand and pulse time, have been measured in previous demonstrations. An accurate assessment of the storage need based upon the microgrid rating provides a means for determining minimized storage costs for microgrids having different ratings and characteristics.

Typical Islanding Scenario: At the time of transition (to islanded) the microgrid has the maximum load - 280 kW of chiller load and 105 kW of motor pump load, on both generators. Depending on the settings of timers T2 and T3 (the default setting for both timers is 30 seconds) as described in Section 6.1, Generators 1 and 2 can take up to 90 seconds to synchronize after static switch has opened. Demonstration 6 showed that T2 and T3 can be set as low as 3 seconds, but for the purposes of the calculation below, the default 30 seconds was used. After synchronization, both generators' power can be ramped up to the maximum power of 190 KW 0ach, this ramp can be as long as another 30 seconds. Hence, with the start of the islanding transition, energy storage has to power a 385 kW load for up to 120 seconds (Refer to Section 6.1). Figure 73 below shows this scenario.

The minimum energy requirement at the point of islanding is calculated as below:

$$Energy = \frac{(280kW + 105kW) * 120\sec}{3600\sec} = 12.83kWh$$

However, in a worst case scenario, if a generator is unable to synchronize for any reason, energy storage has to provide power to the microgrid for another 90 seconds. So, energy storage would provide 25.66 kWh. During grid connected mode of operation, the state of charge of 56 kWh energy storage should be greater than 50%.

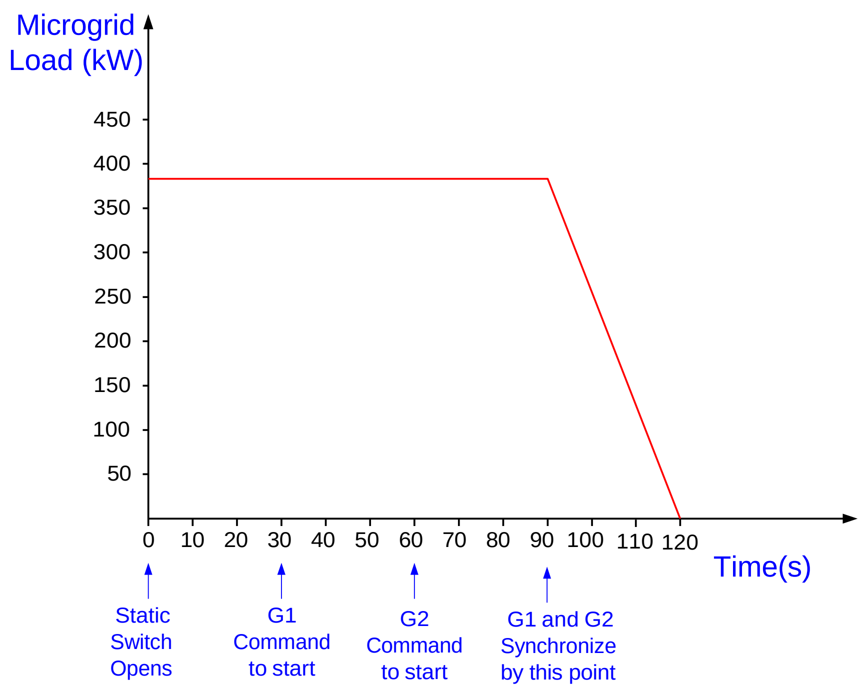

Figure 74: Minimum energy storage requirement during transition from grid-tie to island

Test Description:

- Microgrid islanding data has been used to calculate the minimum storage requirement to meet peak power demand during islanding.
- Chiller is ON during grid connected mode of operation.
- Unintentional islanding occurred and energy storage system supplies the power to the microgrid load.
- To account for the intermittency of renewables, any power they contributed to the microgrid was treated as if it had been sourced from energy storage. For instance, in the test below renewables were producing about 20kW, for determining the required storage capacity this power was considered to have been part of the power the battery needs to produce in order to meet the storage requirements, as if the renewables were not making any contribution.

- The energy storage should be able to provide power to the microgrid until both generators start and deliver power. Hence, the energy storage requirement is calculated from the point of islanding to the point of energy storage power goes to zero after both generators started delivering power.

Results:

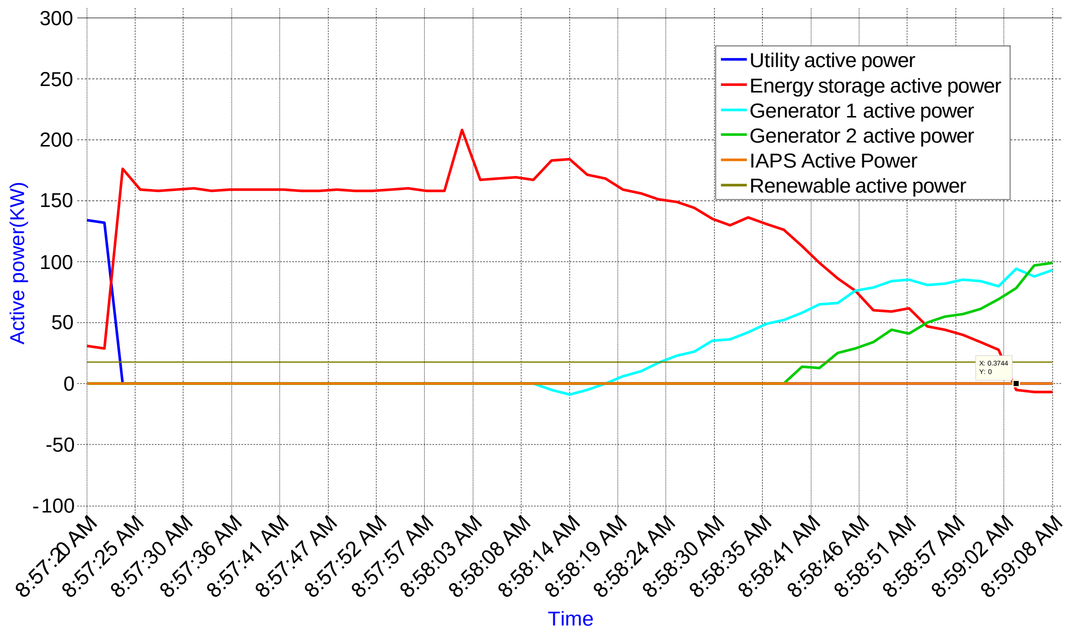

Figure 75: Active Power of utility, energy storage inverter, generator 1, generator 2 and renewables; during islanding operation

Conclusion:

The cycle life of the power optimized battery for a 50% SOC discharge (from "fully charged" roughly 80% SOC) is 15,000. For a 10% discharge it is 170,000 cycles. Over the course of a 51 day monitoring period, 18 power quality events where recorded by the Fluke 1750. This translates to 128.9 unintentional island events annually. Given that this battery is suitably sized for peak power for the load, and maximum kWh for the islanding event, the resulting cycle life (105 years for 50% SOC discharge) is more than adequate for this application.

6.13 Demonstration 13: Assessment of application areas within DoD infrastructure

Purpose:

Identify DoD sites that could benefit from microgrids with power optimized storage, and their potential microgrid power needs for strategic missions. This assessment will be an initial estimate of the potential DoD market for microgrids with power optimized storage. These would be facilities with significant existing on site generation and/or renewables.

Data:

A series of applicable technology transfer targets are listed to include DoD installations with existing and planned microgrid operations. Prime technology transfer targets are sites that have been identified based on a combination of high energy costs, energy security challenges, and planned/proposed microgrid initiatives.

The following are sites that could benefit from microgrids using the features technology demonstrated in this project.

Table 23: Sites that could benefit from microgrids

Site	Technology Need	MW Load	Status of Implementation
Ft. Carson, CO	Distributed Storage inverter technology to replace/upgrade legacy inverters	2-3 MW	System Existing
Twenty Nine Palms, CA	Distributed Storage inverter technology to replace/upgrade legacy inverters	5 MW	System Existing
Miramar MCAS	Direct application of power optimized storage technology	6-8 MW	Planning (Conceptual)
JBPHH, HI	Direct application of power optimized storage technology	5 MW	System Existing
PMRF, HI	Direct application of power optimized storage technology	2-3 MW	System Existing
Presidio of Monterey	Direct application of power optimized storage technology	3-4 MW	System Existing

Table 24: Sites that could benefit from microgrids

Site	Technology Need	MW Load	Status of Implementation
Ft. Sill, OK	Distributed Storage inverter technology to replace/upgrade legacy inverters	5 MW	System Existing
Ft Bliss, TX	Distributed Storage inverter technology to replace/upgrade legacy inverters	3-5 MW	System Existing
Finneyagin, MCB Guam	Direct application of power optimized storage technology	5 MW	Planning (Conceptual)
Naval Base San Diego; and data centers at Naval Base Coronado and Point Loma.	Direct application of power optimized storage technology	6-8 MW	Planning (Conceptual)
PMRF, HI	Direct application of power optimized storage technology	2-3 MW	System Existing
HECO (Pub Utility, non DOD)	Direct application of power optimized storage technology	50 MW	System Existing

The following is a more detailed description of the prime candidate sites for the demonstrated technology. These will have the greatest benefit/impact having microgrids with the proposed technology.

Miramar MCAS, CA: A new microgrid is being planned at Miramar MCAS for implementation in FY16 timeframe. This will be one of DoD's largest microgrid investments on the order of $15M. This will be an energy security microgrid to incorporate renewables including landfill and PV resources.

Joint Base Pearl Harbor Hickam, HI (JBPHH): Distributed inverter technology can be implemented in an existing circuit level SPIDERS microgrid at JBPHH that incorporates 2 MW of diesel generation, 150 kw of PV, a waste water treatment plant with 1 MW of load. The SPIDERS microgrid is configured to accept additional infrastructure improvement including energy storage and distributed inverter technology. Energy cost greater than $.25/kWh.

Pacific Missile Range Facility, Kauai, HI: PMRF has significant energy security and quality challenges at a single circuit from Kauai Island Utility Cooperative serves the base at the end of the feeder with no redundancy. As a consequence, the installation routinely transitions to installation back up power during missile testing and other energy intensive activities. Near-by renewable energy includes methane based landfill gas and PV. Energy cost greater than $.45/kWh.

Finneyagin MCB, Guam: This is a Marine Corp Base (MCB) in Guam that is being planned and designed by NAVFAC. It will support a number of critical operational missions for both Navy and Marine Corps in the Pacific. Load estimated at 4-6 MW. Energy cost greater than $.35/ kWh.

Twentynine Palms MCB, CA: An ESTCP funded activity to incorporate microgrid technology across PV, chilled water, energy storage, chilled water, CoGen, and fuel cell technology over the installation electrical distributions system. Distributed inverter technology can be installed to interconnect the energy storage or PV to the microgrid.

US Army Ft. Sill Lawton, OK: Eaton proposed repurposing of microgrid of this project and expansion to a total of 1.8MW. The expansion of the microgrid includes integration of legacy generators in the waste water treatment plant to the microgrid in building 5900 and would include the load presented starship (dormitory) 6007. The microgrid will be able to handle the increased load with the addition of low cost AGM type energy storage.

7 COST ASSESSMENT

The microgrid technologies to be demonstrated in this project hold enormous promise to the DoD. Successful implementation of this technology will provide hard data that:

- Power storage systems provide the lowest cost power surety/reliability microgrid solution.
- Microgrid enabled renewables (using the microgrid compatible inverter) provide an energy efficient alternative to existing microgrid approaches, where fuel based sources are the mainstay.

Some of the specific and measurable benefits to the military include; Improved energy security through reduced down time for critical loads, 67% reduction in acquisition costs for required microgrid storage systems, ability to integrate legacy generators into microgrids, reduction in overall energy consumption, offset energy demand from the grid, on-site renewable energy generation, lower energy cost, reduced disposal or recycling costs, and decreased carbon emissions.

The system is capable of accepting different types of renewable energy sources, thus the renewable energy source used can be determined and sourced based on geographical location. Because this technology is not geographically limited, it can easily be employed at any DoD or civilian facility worldwide.

The demonstration will develop the technical and financial use case for implementation of this technology in microgrid projects planned throughout the DoD. Important metrics to be measured during the demonstration and post demonstration analysis to be conducted is discussed in detail in section 3 above. Eaton is working with US Army ERDC CERL personnel supporting the project team to provide an analysis and assessment of application of the demonstrated technologies from a DoD perspective. This will provide data supporting the expected DoD benefit of the technology, as well help facilitate the technology transition plan.

The current alternative approach to power optimized storage is utilizing costly energy storage systems, such as flow batteries, lead acid or other chemistries. For a comparable application as being demonstrated in this project, the DoD installation would have to purchase an energy storage system with an initial acquisition cost near $600,000. Additionally, over time the battery cells will have to be replaced or refurbished as they will degrade over time. While this is true for the power optimized solution as well, the quantity of energy storage to be replaced is far greater than that of the power optimized system. Finally, the power optimized solution will be less expensive to dispose of at the end of life, and it will be possible to recycle the lithium cells in the system.

Reduction in Energy Storage System Cost

Energy Optimized Storage System:

Eaton is currently completing a microgrid demonstration at Fort Sill (for a CERL sponsored project). The demonstration is a 400kW microgrid with solar, wind, Natural Gas (NG) generation and an energy storage system based upon a 500kVA continuously rated inverter, and

a ZBB flow battery system rated for 250kW for 2 hours (and 400kW for 3 minutes). This system can power 250kW of the islanded microgrid for two hours, supporting microgrid load during a long term islanding situation with a low emissions source. As shown in Table 25, the cost for this traditional energy optimized storage and inverter solution is $600,000. (Note: The energy storage at Fort Sill was actually leased for this demonstration and not purchased due to the high capital costs and development nature of the project).

Table 25: Cost Comparison of Storage and Inverter Systems

	Storage System	Inverter	Total
Energy Optimized Flow Battery Storage	$480,000	$120,000	$600,000
Power Optimized Storage with Transient Inverter	$118,000	$80,000	$198,000

The traditional energy storage currently used at Fort Sill can be replaced by a power storage inverter which is a 250kW continuously rated unit, modified to have a transient 400kW one minute rating. The storage (Li-ion battery based) is sized for providing 400kW for one minute. This storage system will allow for ride through during loss of the utility. It will also enable the PV system to power the islanded microgrid during short term clouds passing over the PV system or load steps without starting the generator units. As shown in Table 25, the cost for the power optimized storage with transient inverter is $198,000 (or 33% the cost of traditional energy optimized storage).

The data provided in Table 25 can be extrapolated linearly as well. In other words, the cost of energy optimized flow battery storage for a 6-8MW microgrid will be $9-12M and the cost of power optimized storage will be $3-4M. Based upon demonstration results, these costs will be updated in the projects final report.

Battery Lifetime

Based upon available vendor data the nLTO battery lifetime will be at least as long (5 years) as that of the flow battery cells.

- Flow Battery: The manufacturers (ZBB) table states that Zinc-Bromide flow batteries have a stack (cell) life of 5-6 years, after which they require replacement.
- nLTO Battery: For Eaton’s specified power cycling application needs, the vendor has indicated at least 5 years life for the maximum duty condition, and greater than 5 years for nominal duty conditions. See the Tables below (Eaton requirement, Vendor response).

Table 26: Battery Vendor Endurance and Lifetime Table A

Endurance and Lifetime		
	Maximum Duty	**Nominal Duty**
Ambient Temperature	45°C	35°C
Max. Duty Cycle (an unusual event for 1 hour only at a time)	10 cycles per hour	5 cycles per hour
Cycle Life (1): 400 kW with 60 sec discharge, 60 sec charge	3,000/2 years	Vendor to specify
Cycle Life (2): 400 kW with 30 sec discharge, 60 sec charge	8,000/2 years	Vendor to specify
Cycle Life (3): 250 kW with 60 sec discharge, 60 sec charge	8,000/2 years	Vendor to specify
Operational Life	Vendor to specify	Vendor to specify

Table 27: Battery Vendor Endurance and Lifetime Table B

Endurance and Lifetime		
	Maximum Duty	**Nominal Duty**
Ambient Temperature	Cell Temp 20°C / 55°C	Cell Temp 20°C / 55°C
Duty Cycle	10 Cycles for 1 Hour	5 Cycles for 1 Hour
Cycle Life (1): 400 kW with 60 sec discharge, 60 sec charge	Altairnano's chemistry and battery cycle life is based around DoD in a duty cycle not kWh throughput as with other chemistries. All systems proposed are designed to meet longer than 5 year life in use. Life is dependent on actual duty cycle DoD, without an estimated continuous usage life has been estimated based on maximum duty cycle of 400 kW cycles. Please see duty cycle modeling for each system for DoD (SoC changes) during stated duty cycle. As a note, aging has been modeled as 5 years, 24 hrs/day, 365 days/yr, with 10 cycles per hour. (438,000 cycles). Also please refer to the Cycle Life vs. DoD chart for further reference.	
Cycle Life (2): 400 kW with 30 sec discharge, 60 sec charge		
Cycle Life (3): 250 kW with 60 sec discharge, 60 sec charge		
Operational Life	5 years	>5 years

Also from the vendor (Altairnano), the life of nLTO batteries is 16,000+ 100% cycles, and 20 year calendar life (at 25C). Section 2, and in particular Figure 9 of the Demonstration Plan discuss this.

Also per the vendor:

- Altairnano has completed tests involving over 16,000 cycles of continuous charging and discharging of the battery cells and found minimal degradation to the product. The cells still retained over 80% of their original charge capacity at the end of these tests. This

cycle life is an order of magnitude greater than any other lithium ion battery technology, making Altairnano's nLTO technology the best technology suited for long life applications.

- The degradation of Altairnano batteries due to calendar life is also much better than other lithium technologies, losing less than 1% of their energy capacity after 25 years, making it less likely that the batteries will ever need to be replaced.

Projected Economic Benefit

Eaton has conducted a preliminary analysis of the projected economic benefit of the project in terms of simple payback and savings-to-investment ratio over a 5, 10 and 20-year period using the NIST BLCCA process. Table 28 and Table 29 below show the results of our analysis.

Table 28: Simple Payback Ratio

SPB:	
-1340.000	Years

Table 29: Savings-to-Investment Ratio

SIR Calculations:	
@5yrs	-0.00543360
@10yrs	-0.00600229
@20yrs	-0.00747373

The results from this analysis are unusual because the alternative in the analysis (the Eaton Power Optimized System) is significantly less costly from an initial acquisition and ongoing operational and capital replacement standpoint than the base case (Energy Storage), with equivalent energy cost savings. The results indicate that the proposed system is immediately profitable.

An easier way to look at this is to consider the Eaton Power Optimized System as the base case with a flow battery energy storage system as the alternate case. This analysis would show if the added projected energy savings from being able to run the microgrid from the energy storage would offset the initial investment cost. In this scenario, we see (in Table 30 and Table 31) that the payback period is over 22 years and the savings-to-investment ratio is between 0.3 and 0.4 (note: an alternative is considered economically justified relative to the base case when the SIR is greater than 1).

Table 30: Inverse Simple Payback Ratio

SPB:	
22.396	Years

Table 31: Inverse Savings-to-Investment Ratio

SIR Calculations:	
@5yrs	0.32511029
@10yrs	0.35913695
@20yrs	0.44717835

This inverse case calculation further supports our analysis that the 66% savings in initial system cost for the Eaton Power Optimized Storage system justifies this approach relative to other more costly energy storage approaches.

Preliminary Analysis of the Projected Economic Benefit Inputs and Assumptions

Table 32 provides the input data and assumptions made for the SPB and SIR calculations. Note that for the results given in Tables 3 and 4, the energy storage system is the Base Case and the Eaton Power Optimized System is the alternate case. To achieve the results in Table 30 and Table 31, the cases were switched, however that data table is not provided below as it is a mirror of the information in Table 32.

Table 32: Input Data for SPB and SIR Calculations

Data Table		
	PV Base Case	PV Alt Case
Energy Cost (1) @ 5 Years	$ 83,580	$ -
Energy Cost (1) @ 10 Years	$ 155,676	$ -
Energy Cost (1) @ 20 Years	$ 271,876	$ -
Water Cost	N/A	N/A
Initial Cost	$ 600,000	$ 198,000
Residual Value @ 5 yrs	$ 237,217	$ 88,072
Residual Value @ 10 yrs	$ 183,345	$ 54,626
Residual Value @ 20 yrs	$ 57,582	$ 16,400
OM&R Cost @ 5 yrs	$ 2,290	$ 916
OM&R Cost @ 10 yrs	$ 4,265	$ 1,706
OM&R Cost @ 20 yrs	$ 7,449	$ 2,979
Capital Replacement Costs @ 5 yrs	$ -	$ -
Capital Replacement Costs @ 10 yrs	$ 185,669	$ 32,603
Capital Replacement Costs @ 20 yrs	$ 290,361	$ 53,192

The calculations used for this analysis are those included NIST BLCCA process handbook; specifically, Equation 6.13 for the SPB and Equation 6.4 for the SIR. Present values were used for all SIR calculations.

Energy Savings Calculation: The energy savings calculation represents the energy cost savings if you were able to utilize energy storage to power the microgrid for a specified period. Given that theoretically you could use energy storage to supply 250 kW for two hours, we extrapolated this out for an annual savings assuming this energy was available every day of the year and the energy cost was $0.10 per kWh. The present values of those savings over 5, 10 and 20 year periods are included in Table 32.

There is no anticipated water savings associated with this technology.

Residual Value Calculation: We assumed a total expected life of the system to be 24 years. The inverter portion of the system was straight line depreciated over that 24 year period such that the residual value at 24 years is $0. There is an 8 year life on the energy storage portion of both systems. Assuming two system overhauls (at 8 and 16 years), the book value of the initial

energy storage components and capital replacement costs were straight line depreciated over individual 8 year periods, again so that the residual value at 24 years is $0.

OM&R Calculations: This model assumed a minimal amount of ongoing OM&R costs annually.

Capital Replacement Calculations: This model assumes both systems have 70% of their cells or modules that need to be replaced every 8 years. Additionally, the model assumes some reduction in acquisition costs of battery technology over time to make this replacement cost more affordable. We assumed a 50% cost reduction (from present) for the first lithium battery replacement ($82,600 current replacement will be $41,300 in 8 years). We assumed a further 20% cost reduction for the second lithium battery replacement ($33,040 in 16 years). For flow battery technology we do not anticipate such a learning curve and volume increase to drive down costs. We assumed a 30% cost reduction (from present) for the first flow battery replacement ($336,000 current replacement will be $235,200 in 8 years). We assumed a total 50% cost reduction from present for the second flow battery replacement ($168,000 in 16 years).

7.1 COST MODEL

This model addresses the costs related to the demonstration of the technology (power optimized battery, storage inverter, solar PV and associated controls). Costs related to installation and verification of the Ft. Sill microgrid for CERL is not considered.

Table 33: Microgrid Modified for Power Optimized Energy Storage

Cost Element	Data Tracked During the Demonstration	Estimated Costs
Hardware capital costs	Power optimized battery, storage inverter, solar PV system and associated controls	$418,755.17
Installation costs	Eaton Electrical System & Services - labor and materials, including design	$672,436.01
Consumables	Natural Gas (Generators 1 & 2) Only consumed when islanded	Oklahoma Natural Gas Industrial Price: 10.11 USD/thou cf for Aug 2014
Facility operational costs		Unknown
Maintenance	• Monthly Generator Exercise and Battery Maintenance Charge • 2 hours monthly	Ft. Sill DPW hourly labor cost is not known.
Hardware lifetime	Estimated component lifetime is examined previously in this section.	

Operator training	Estimate of training costs (4 hours training session)	Trainer travel and labor:$1500.00 Trainee(s): Ft. Sill DPW hourly labor cost is not known.

- Power Optimized Battery:
  The 400kW battery higher volume cost is estimated at $118,000 or $295 per kW. When a battery size is determined for a new system employing the technology the “per kW” cost can be used to estimate the battery cost. As this battery technology matures the per kW cost are expected to decrease.

- Microgrid Capable Storage Inverter:
  The inverter used in this demonstration was rated at 500kW and a custom assembly for the CERL Ft. Sill microgrid project; it had a cost estimated at $120,000. For future uses of the technology microgrid storage inverters specifically tailored to power optimized battery applications would be used. In the case of this microgrid, an appropriately rated storage inverter is estimated to have a cost of $80,000. In future systems, the inverter capacity will need to be determined in accordance with the battery rating requirements.

- Solar PV Commercial Size Array:
  The technology demonstrated was designed to include significant support from PV. The PV industry rule-of-thumb for installed cost per watts of a commercial size PV system is $4.60. For the 86kW array of this demonstration, $4.60/Watt translates to $396,000. As with the other system components described above, array size will need to be determined to serve the purposes of the application.

- Microgrid Controls for Legacy Generators:
  Controls must be designed and programmed such that the technology can work in cooperation with the balance of microgrid components. Code design and programming of the PLCs used in the system had a cost of $29,010. CAT_ISO controller programming costs were $32,000.

7.2 COST DRIVERS

The power optimized battery technology is an inherently less costly energy storage method than the typical energy optimized batteries frequently used in microgrid installations. A comparison of the main cost drivers of these two technologies are described in Section 6, Demonstrations 7 and 8. Power optimization reduces the rating and physical size of energy storage, lowering procurement, inverter and installation costs. The cost driver is therefore the cost of the lithium-titanate battery technology which is expected to decrease as it matures and comes into greater levels of production.

7.3 COST ANALYSIS AND COMPARISON

Table 34 below provides a budgetary estimate for expansion of the existing Ft. Sill microgrid using the ability to support natural gas generators with a power battery and microgrid controls to manage renewable and other generating sources. The expansion of the microgrid includes integration of legacy generators in the waste water treatment plant to the microgrid in building 5900, and would encompass a total power of approximately 2MW. The implementation of this over a mile-long 13.2kV line will be a new milestone for microgrid technology at Fort Sill.

Scope and Cost

1. Install a pole-mounted re-closer to island the starship 6007, building 5900 and the waste water treatment plant
2. Modify chiller control to enable (reduced voltage) starting with the microgrid
3. Add low cost storage to support larger distributed load
4. Add load shedding and communications across the buildings

Table 34: Task Cost Estimate

	Description of task	**Cost Estimate**
1	Electrical and control system design	$35,000.00
2	New hardware to be added	$290,000.00
3	Update microgrid and WWTP generator controls	$175,000.00
4	Installation and wiring of the new hardware	$250,000.00
5	Integration, testing, and commissioning	$255,000.00
6	Demonstration and training	$35,000.00
7	Program management	$70,000.00
	Total Budgetary Estimate	**$1,110,000.00**

This expansion would enable a higher power capacity microgrid offering extended islanded operation with critical loads included. As lower cost power optimized storage is applied, the overall costs become dominated by site construction costs typical of any electrical expansion or refurbishment, and independent of storage technology employed.

8 IMPLEMENTATION ISSUES

The following are microgrid site implementation issues and technology lessons learned that should be addressed early in future similar projects, or will benefit the future implementation of the demonstrated technology.

8.1 Reduced Voltage Starting (Chiller)

Starting the chiller, even the smaller chiller #3 unit, is an abrupt reactive load step that taxes the utility grid briefly as well as causing mechanical stresses on all connected equipment. For the microgrid, chiller starts cause voltage and frequency fluctuations that constitute power quality events.

Lesson Learned

It is Eaton's recommendation that for large inductive loads such as large motors and chillers, reduced voltage starting techniques be used where possible.

8.2 End User Concerns

Eaton completed the on-site activities for the demonstration at Ft. Sill. One of the final tasks was to provide microgrid system operator training to Fort Sill DPW (Department of Public Works) and other staff that might be involved with periodic maintenance of the microgrid. It became clear over the course of the training that no individual or department had clear responsibility for ownership and maintenance of the system.

Lesson Learned

Eaton's recommendation is that the responsible owner and future operator be identified early in the deployment process so that the individual or group "owner" is familiar with the microgrid as the installation unfolds to acquire a fuller understanding of the technology, its intended use and future maintenance issues.

Eaton has left the microgrid in an inactive mode: static switch open and bypassed, storage inverter and batteries are off, NG generator's automation disabled. All renewable sources are connected and operating. The training provided allows a user to bring the inactive components online, intentionally island the microgrid, apply a resistive load to the generators and perform maintenance charge and balancing of the batteries. These operations are the minimum required to maintain equipment in an operational state, and allow for expanded use in a future microgrid expansion.

8.3 Site Load Availability

Chiller #3 served as the primary microgrid load, but other HVAC equipment (cooling tower, air handling equipment for HVAC in Starship buildings, etc.) that are required to make the chiller operations useful were not included as part of the load. Having the microgrid drive these additional loads, to control a full system, would have enabled a more effective demonstration, and also would have allowed Eaton to perform the longer term (months of continuous operation) demonstration tests that had been planned as part of the original objectives. Further, the chiller was not available to run as a load during the colder months of the year. It is highly

recommended that the Fort Sill microgrid be expanded to include all loads on a full MV feeder on the east side of the post. This would enable extended operation in islanded mode with a full spectrum of sources and loads within the autonomous island.

8.4 Lesson Learned – Multiple Packs of Parallel Batteries

The Battery Management System (BMS) calculation of SOC is based on the SOC of all the racks. If the SOC of one rack is low, that affects the SOC of the entire system. Isolating a bad rack is more efficient than keeping it in the microgrid with its partial capacity.

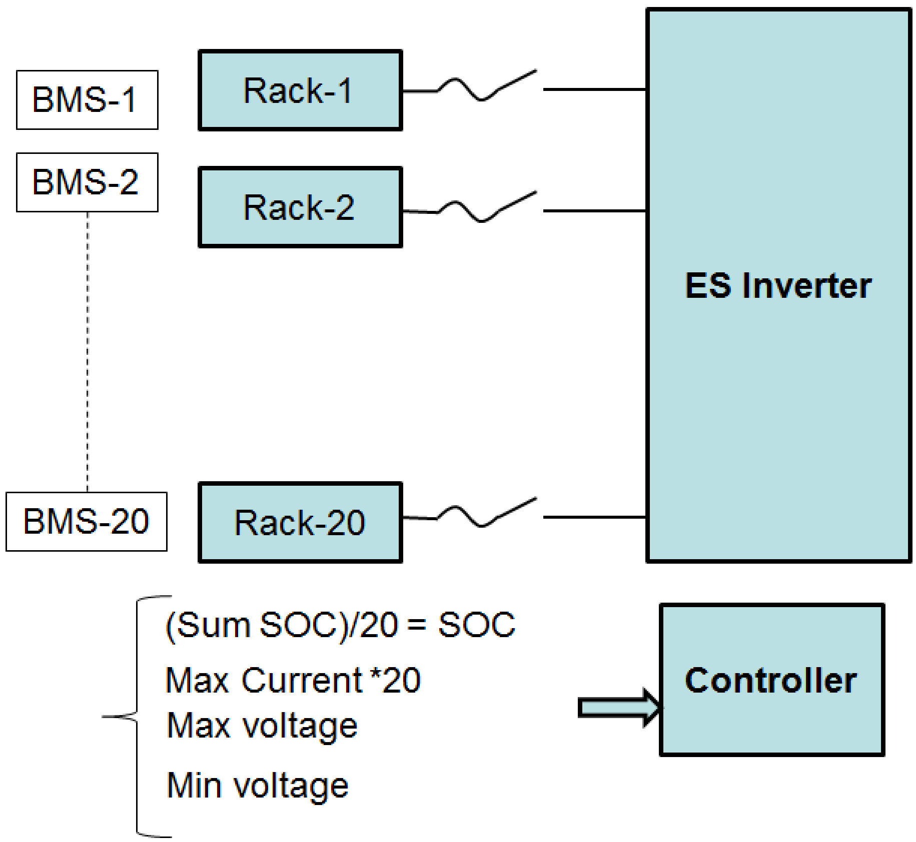

Figure 76: Deficient Batteries Maintained in Parallel Produces a Negative Effect on Entire Battery System

This was discovered when a module (24V battery) in one of the two racks was consistently showing a lower than average SOW. Replacement of its local BMS controller corrected the issue.

9 REFERENCES

1. Olson, Gary. *Paralleling Dissimilar Generators: Part 1 – An Overview.* Power topic #9015. Technical information from Cummins Power Generation; White Paper.
2. IEEE Standard 1547
3. Georgia Tech Fort Sill Microgrid paper

10 APPENDICES

Appendix A: Points of Contact

Point of Contact	Organization	Phone & E-mail	Role in Project
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